Condition-Based Maintenance Applied to Rail Freight Car Components --- The Case of Rail Car Trucks

by

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ABSTRACT

Maintenance of the various components of rail freight car continues to be an extremely important concern to railroad decision makers. Varied policies for rail freight car maintenance not only have an impact on rail car availability but also effect the operating cost, freight damage rate and safety.

In this research, condition based maintenance (CBM) policy is proposed for the maintenance of rail freight car components, especially freight car trucks, in order to obtain the greatest benefits from maintenance activity in the system level. In order to capture all the system level consequences of a given maintenance policy, an economic model based on life cycle cost is used.

Model results show that CBM can save 5% to 12% of life cycle cost relative to two alternative maintenance policies, even when the inspections are not perfect (i.e., a 70-80% correct prediction rate). The sensitivity analysis indicates that the result is quite robust.

This research also addresses the issue of when to use premium trucks and when to use standard trucks. Even though premium trucks are more expensive than standard truck, they have better performance, and longer life. If a freight car is highly utilized, premium trucks have about 5% lower life cycle cost comparing to standard trucks under the preferred CBM maintenance policy.

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Chapter 1

INTRODUCTION

1.1. Problem Statement

Maintenance of the various components of rail freight car continues to be an extremely important concern to railroad decision makers. Freight cars are an important and integral part of the rail transportation system. Varied policies for rail freight car maintenance not only have impact on car availability but also effect operating cost, freight damage rate and safety. The most commonly used policies in practice are to replace upon failure or to replace periodically. Problems associated with replacement upon failure are that it would result in a higher operating cost, incur failure cost and also raise safety concerns. For the periodic replacement policy, it is hard to decide the right life limit at which components will be replaced. The same components on different cars may have different lengths of physical lives because of different usage patterns. If the replacement limit is conservative, a risk exists that the component may be replaced under the scheduled maintenance regime well before its useful life has elapsed; this would result in excessive and unnecessary maintenance and higher life cycle costs. In the cases where the replacement limit is too optimistic, many components will fail before being replaced, and costs will be similar to replace upon failure.

In this research, condition based maintenance (CBM) policy is proposed for freight car components in order to obtain the greatest benefits from system maintenance. CBM is the strategy by which maintenance is undertaken only when the component or system reaches a particular state or condition, usually one which is believed to be a precursor to in-service failure. CBM allows railroads to replace a component after it has had a fairly long life, but before it deteriorates so much as to cause sharply increased operating cost or a significant risk in-service failure. CBM therefore is like to result in the lowest life cycle cost among the three policies.

In this thesis, the maintenance of freight car components is our general concern while maintenance of freight car truck is studied in detail because freight car trucks present a useful example of many of the problems associated with developing and implementing an effective CBM program. At the heart of CBM is the ability to measure or estimate the true condition of the component, and to determine what action to take in response. The freight car truck is the lower part of freight car, which acts as an interface between the car body and the rail track and enables the movement of the cars. In order to apply CBM to freight car trucks, the true internal conditions have to be known or detected which is a difficult because the internal parts are located under the car bodies and cannot be observed directly without lifting the car bodies off the truck.

In order to capture all the consequence of a given maintenance policy in the system level, life cycle cost is used. Life cycle cost is the sum of initial cost, operating costs, inspection cost, replacement cost and failure cost, divided by life of the component. The reason that operating cost is being included is because different maintenance policies would result in different conditions for freight car trucks over time, and different truck conditions have different effects on the operating costs.

An economic model is developed in order to compare the impacts on life cycle cost under those three maintenance policies and to illustrate how CBM can be implemented for freight car truck maintenance. The same model is used to address the issue of when to use premium truck and when to use standard truck. Generally speaking, premium trucks have higher initial cost but better performance than standard trucks do. For new cars and for replacement of trucks on old cars, a question raised in practice is which kind of truck is more economical. This would be influenced by the type of commodities the cars carry, the usage pattern of the cars, the current condition of other part of car components, and other factors.

1.2. Research Contributions

This research makes three contributions to the state of knowledge about transportation systems and vehicle maintenance. First, it systematically evaluates various maintenance policies being used in rail freight car truck maintenance. It does this by analyzing the advantages and disadvantages associated with each maintenance policy and then demonstrating this in a economic model of freight car trucks.

The second contribution is that a framework of applying CBM to rail freight car components is developed. In the case of freight car truck, it shows that CBM would result in the lowest life cycle cost among three policies.

The third contribution is that the issue of when to use premium truck and standard truck is addressed by employing the economic model of freight car truck. This provides fresh insight from a system point of view.

1.3. Structure of the Thesis

This thesis is organized along the line of general discussion of maintenance theories, modeling and application, and is illustrated in the flow chart in Figure 1.1.

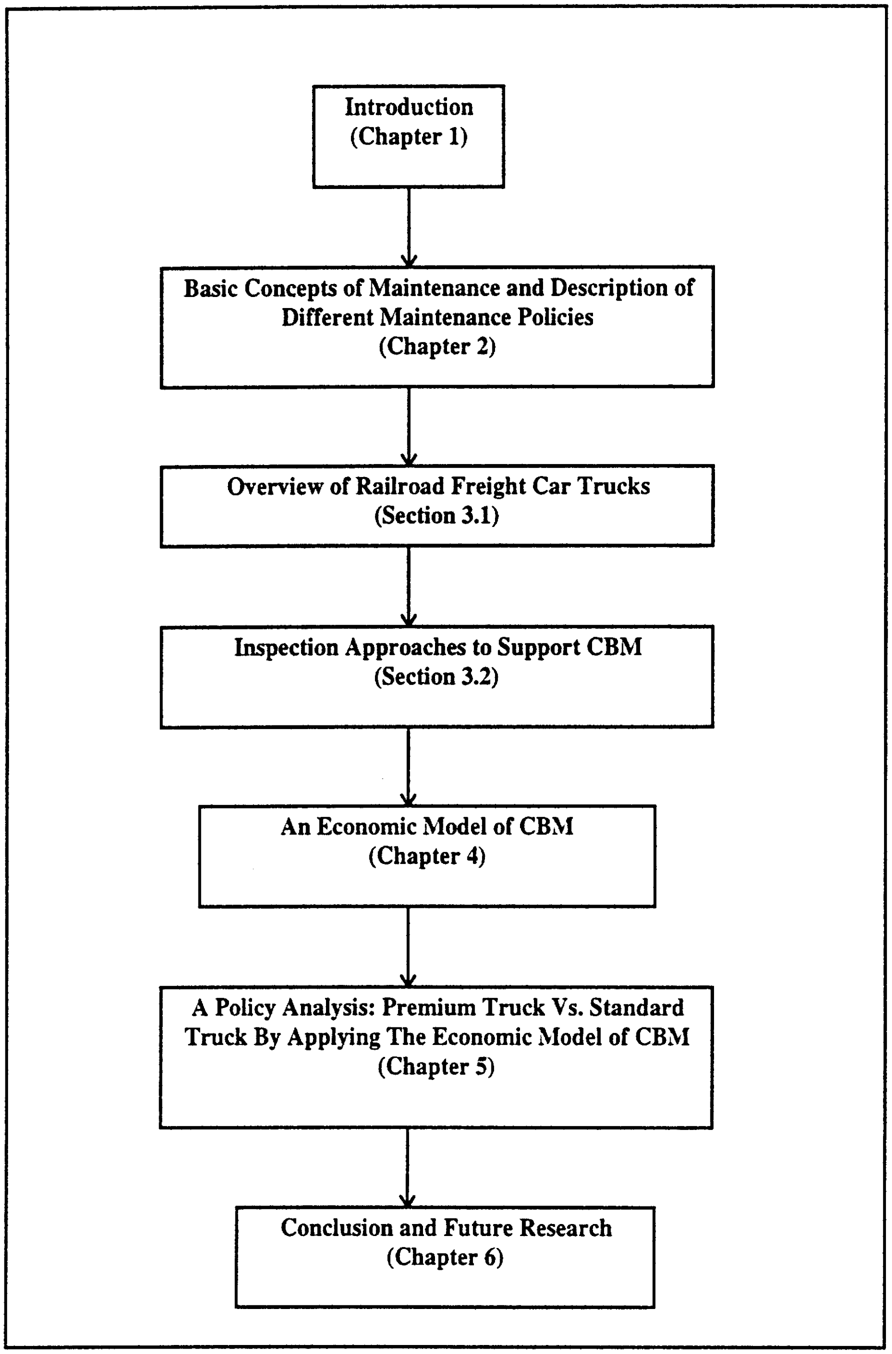


Figure 1.1 Thesis Structure

Chapter 2

Review of Maintenance Policies

This chapter first reviews the basic concepts of maintenance and analyzes the advantages and disadvantages of common maintenance policies. It then describes some key issues of applying CBM, i.e., sensitivity and specificity of inspection techniques. Finally, it summarizes some applications of CBM in non-rail industries to give some insights on applying CBM to rail car components.

2.1. Definition of Maintenance

Maintenance is a combination of any actions carried out to retain an item in, or restore it to, an acceptable condition in a cost effective manner [Williams *et al.*, 1994].

The key phrases are “an acceptable condition” and “in a cost effective manner”. In the case of the maintenance of rail freight car trucks, the condition of trucks not only affects the quality of service railroads provide, but also affects the overall operating cost (as will become clear in later chapters). An acceptable condition for rail freight car trucks therefore implies a state of truck in which the system provides a safe and reliable service with a low operating cost. This shows that when considering a maintenance program or policy for rail freight car trucks, railroads must take account of both the performance of a truck in terms of service and the impact it has on operating cost.

If railroads have little concern on other factors, they can maintain rail freight car trucks in good condition by frequently replacing them with new trucks. However, this will result in a low utilization of the components and more down time for the freight cars.

In order to take above concerns into account, life cycle cost must be used. Life cycle cost is the sum of initial cost, operating cost, inspection cost and maintenance cost, divided by life of the component. It can be calculated as follows,

$$LCC = \frac{\text{init\_cost} + \text{op\_cost} + \text{insp\_cost} + \text{instal\_cost} + \text{fail\_cost}}{\text{life}}, \tag{2.1}$$

where LCC is the life cycle cost for a component; init_cost is the cost used to purchase the component when it was new; op_cost is the additional operating cost due to the component, this may become more clear when explained in chapter 4; insp_cost is the cost associated with inspection for some maintenance policy; instal_cost is the cost associated with the repair/replacement of the component; fail_cost is the cost caused by the failure of the component.

Generally speaking, a maintenance policy which results in a longer life and lower cost in one or more above cost components is preferred.

2.2. Alternative Maintenance Policies

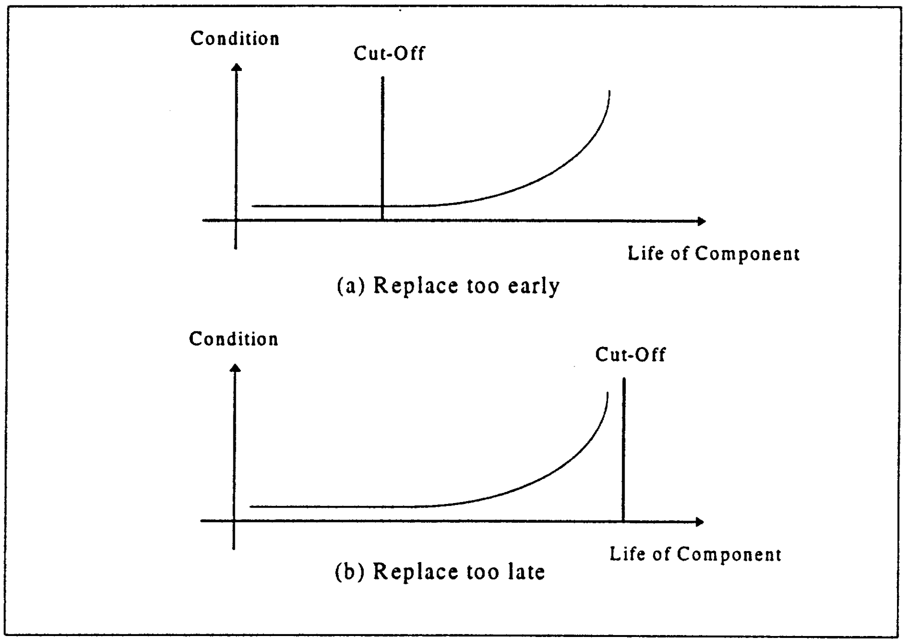
In this section, we describe two common maintenance policies, i.e., periodic replacement and replace upon failure. We then analyze the advantages and disadvantages associated with these policies.

Replace upon failure is a policy that can be characterized as “do nothing until it breaks”. This policy allows the components maintained to have the maximum life span. The problem associated with it is that it would result in a higher operating cost, failure cost and, for some components, may cause of safety concerns. This policy is applied to number of low cost or non-critical components, such as tie.

This is generally only a reasonable strategy when the true condition is not knowable, the components is not subject to an increasing failure rate, or the costs of failure are low relative to the costs of replacing unfailed components. If the components fail randomly and provide no prior indication of impending failure, this type of maintenance remains the only option. Even if the condition of component can be obtained, but only through a costly inspection method, and the costs of failure are lower than the cost of inspection, then this replace upon failure strategy is still justified. Another case involves production processes with certain time cycle or season feature. For example, some manufacturing systems work in weekly basis, 5 days production, two weekend days off; or in daily basis, works from 8:00 AM to 5:00 PM. If the cost of failure for some component is low and replacing the unfailed components will interrupt the normal production, it may be better off to perform the maintenance activity in off production period.

Periodic maintenance is a policy that system components are replaced in a predetermined interval. In an ideal situation, the predetermined interval is an optimal one for some components in every rail freight car so that the service reliability is high and operating cost is low. However, in reality, this optimal interval is hard to obtain. Even for the same components, they may have different physical lives because of different usage patterns. Figure 2.1 shows the two extreme cases. If the replacement limit is conservative, a risk exists that the component may be replaced under the scheduled maintenance regime well before its useful life has elapsed (figure 2.1(a)). This result in the conduct of excessive and unnecessary maintenance and subsequent costs. In the cases where the replacement limit is too optimistic and the components fail before being replaced (figure 2.1(b)), costs similar to replacement upon failure will occur.

Figure 2.1 Periodic Replacement Policy



2.3. Condition Based Maintenance

Condition-based maintenance (CBM) is the strategy by which maintenance is undertaken only when the component or system reaches a particular state or condition, usually one which is believed to be a precursor to in-service failure. Because CBM allows railroads to replace a component of a rail car at the right point where it has had a fairly long life and where continued use would cause sharply increased operating cost and further might cause in-service failure, CBM would result in the lowest life cycle cost among three policies.

The definition of CBM implies there are three critical issues for CBM to be successful. The first critical issue is the accuracy of the inspection. CBM requires that there is some means of determining the true condition of the component, this is usually done by inspection. The accuracy of the inspection will directly affect the result of CBM.

The second critical issue is the inspection interval. Every inspection has a cost associated with it. This normally includes the labor cost involved in inspection; some times there is a cost for out off service time if the normal production has to be interrupted for inspection. If the inspection interval is short, the number of total inspections will be high. The inspection cost will be high also. On the other hand, if the inspection interval is not short enough to catch the defect, the component will fail, and there are costs associated with component failure.

The last critical issue is the condition limit. The condition limit has affects on the life of the component and the operating cost of the system. Here the condition refers to wear, good components have low wear and bad components have high wear. If the condition limit is set very low, then components will have a shorter life. On the other hand, if condition limit is set very high, the operating cost will become very high because the condition of component has deteriorated to a level where the system cannot function as it should.

In this section, first, the accuracy of inspection is discussed. Second, some literature on inspection intervals is reviewed. Finally some of the CBM applications are reviewed.

2.3.1. The accuracy of Inspection

In general, when a component is inspected, the true condition of maintained asset may not be obtained with 100 percent accuracy due to varied reasons. Therefore we need some indicators to measure the accuracy of inspection. One obvious indicator is the correctly predicted rate, which is the percentage of the samples that their believed conditions from inspection match their true conditions. However, this indicator is not effective enough to tell the whole story.

Suppose there are 100 samples, of which 90 are in good condition and 10 are in bad condition. However, the inspection results are different: we believe that all 90 samples which are actually in good condition are in good condition, but only 5 of the 10 samples which are actually in bad condition were found to be bad. The overall correctly predicted rate is 95 percent, which is quite good, but we missed half of the bad samples.

In medical examination and inspection literature, sensitivity and specificity are often used to describe the accuracy of an inspection method [Muller *et al.*, 1990]. "Positive" and "negative" are the terms used to described the test result of a medical examination. If a test for a disease is positive, it means the disease is not present. If the test is negative, the disease is present. Sensitivity can be used to describe the ability of an examination to detect the disease if the disease is present indeed. Specificity is the ability to detect healthy people if the people are really healthy. In other words, sensitivity (specificity) tells the probability that an examination finds a person with (without) the disease, given that the person really does (does not) have the disease. False positive rate is the underestimation rate of an examination, and false alarm rate is the overestimation rate of an examination. Here sensitivity and specificity can be helpful to measure the overall effectiveness of an inspection along with the false negative rate and the false alarm rate. They can be calculated by using formulas in table 2.1.

Table 2.1 Sensitivity and Specificity

	Bad (true condition)	Good (true condition)
Bad (predicted)	a	b
Good (predicted)	c	d
Total	a+c	b+d
Sensitivity = a/(a+c) Specificity = d/(b+d) False positive rate = 1- Sensitivity = c/(a+c) False alarm rate = 1- Specificity = b/(b+d)		

In the example above, we had 100 samples, 90/10 split for good and bad conditions. For the 90 samples in good condition, the perceived conditions from inspection were all good. For the 10 samples in bad conditions, the perceived conditions from inspection were 5 good and 5 bad. Then the specificity for this inspection method is 90/90 = 100% and false alarm rate is 100-100 = 0% while the sensitivity is 5/10 = 50% and false positive rate is also 50%.

2.3.2. Literature Review On Inspection Interval

The examinations scheduling problem or inspection interval problem have long been the subject of research in the medical screening field. One of the most effective ways to control a chronic disease is screening - examining seemingly healthy individuals to detect the disease before the surfacing of clinical symptoms and enable early and more effective treatment [Morrrison, 1985]. If it is established that a particular screening procedure is medically desirable, there remains the practical necessary of determining whether of not the costs involved would be worthwhile [Shahani and Crease, 1977]. Clearly in these days of scarce resources it is necessary to search for screening policies that will make the procedures as efficient as possible. Many variables influence the efficiency of a screening program, and inspection interval is one of the most important variables.

Following are reviews of the research on this topic. The reviews will focus more on the methodology, especially on how the problem is structured and formulated, rather than how the solution is derived mathematically. The mathematical solution is important to implement the system, but it varies with the nature of problem. On the other hand, the methodology may be applicable to different applications with justification.

(1) **Optimum Checking Procedures** (1963) by Barlow, Hunter and Proschan

One of the classical and probably one of the most important work on this topic is done by Barlow *et al* [1963]. In that research, it states that the problem of checking or inspection often arises in connection with systems that are deteriorating. It assumes that deterioration is stochastic and that the condition of the system is known only if it is inspected. It further assumes that upon detection of failure, the problem ends. The optimization problem considered here is to minimize the total expected value of the cost of the lapsed time between system failure and its detection and the cost of checking.

As an example consider the problem of detecting some grave physical illness such as cancer by successive medical examinations. Each examination costs money and takes time so we do not wish to examine too often. On the other hand, the longer the time elapsed between occurrence and detection of the condition, the greater the "cost".

Therefore, two costs are considered : (1) each check entails a fixed cost c_1; (2) the time elapsed between system failure and its discovery at the next check results in a cost c_2 per unit of time. Let $N(t)$ denote the number of checks in $[0,t]$ and r_t the time to discovery if the system fails at time t. Then the loss is

$$c_1[N(t)+1]+c_2r_t, \tag{2.2}$$

for a given system with failure distribution F, the expected loss is

$$E(loss)=\int_0^\infty\{c_1[M(t)+1]+c_2E[r_t]\}dF(t), \tag{2.3}$$

where $M(t) = E[N(t)]$.

Any checking procedure that minimizes this objective function is called an optimum checking procedure.

To specify a checking procedure it is sufficient to specify a sequence of random variables $\{Y_k\}$, called the inter-checking times, or inspection interval. If the random variables are identically distributed, the associated checking procedure is called *periodic*. If the random variables are not identically distributed, the checking procedure is called *sequential.* Barlow et al. concluded that periodic checking procedures are optimum over the class of sequential checking procedures only for systems which fail according to an exponential distribution. In this case, the optimum interval is derived based on (2.3) as:

$$x = \sqrt{2c_1 a / c_2}, \tag{2.4}$$

where system failure distribution $F(t) = 1 - e^{-t/a}$, a is the mean time between failures.

Equation (2.4) says that the interval could be longer if the cost of each inspection is higher or the mean time between failures is bigger, while it should be shorter if c2 is higher.

Intuitively speaking, if c_1 is far greater than c_2, then we wish only to check once at the end of period T. Otherwise, we wish to check more often.

If the density $f(t)$ of the failure distribution F is a Polya frequency function of order two (PF2), i.e.,

$$\frac{f(x-a)}{f(x)}$$

is non-decreasing in x for any $a>=0$, then checks occur more and more frequently in time under the optimum procedure. The interval of checking between $k+1$ and k is derived based on (2.2):

$$x_{k+1} - x_k = \frac{F(x_k) - F(x_{k-1})}{f(x_k)} - \frac{c_1}{c_2}, \tag{2.5}$$

when $f(x_1)=0$, $x_{k+1} - x_k = \infty$ so that no more checks are scheduled. The sequence is determined recursively once we choose x_1.

(2) **Inspection Procedures when Failure Symptoms Are Delayed** (1980)

by Sengupta

This paper is an extension of Barlow et al's work in some degree. In Barlow *et al*'s work, systems are assumed to have two states. In this work, systems with three states are considered.

Consider a system that is subject to random failure at time T, where the probability density function of T is $f(t)$. The system is in the "good" state in the interval $[0, T]$ and it makes a transition into the "fair" state at time T. While in the "fair" state, the system does not display any symptoms of failure and only an inspection at a cost c can reveal the failure. If no inspections are held, the system develops some symptoms of failure after another S random units of time where the probability density function of S is $g(s)$. the random variables T and S are assumed to be independent. The epoch $T + S$ is called the self-detection point and, at this epoch, the failure of the system becomes obvious to an observer. On discovery of failure, either by an inspection or due to self-detection, the system enters the "bad" state and no costs are incurred while the system is in the "bad" state. The inspections are assumed to be error free.

An example of such system is a production process that may start producing defective items after some random amount of time. A cost-rate v is associated with the production of defective items and the defect may be detected by an inspection of the product quality. If the situation is not corrected, the product quality gradually deteriorates to a level where it is self-evident to the operator that the system has failed. By inspecting the product quality at some intervals, the operator may be able to reduce the total expected cost over one lifetime of the system. Here is the model formulation.

Let m_2 be the mean of the random variable S (assumed finite). If no inspections are performed, the expected cost is vm_2. If, however, inspections are scheduled at $X = (X_1, X_2, \ldots, X_n, \ldots)$, the expected cost is

$$\begin{aligned} E(X) &= \sum_{i=0}^{\infty} \int_{X_i}^{X_{i+1}} \int_0^{X_{i+1}-t} (ic + vs) g(s) f(t) ds dt \\ &+ \sum_{i=0}^{\infty} \int_{X_i}^{X_{i+1}} \int_{X_{i=1}-t}^{\infty} ((i+1)c + v(X_{i+1} - t))) g(s) f(t) ds dt \end{aligned} \tag{2.6}$$

where $i = 0, 1, 2, \ldots, N$ and $X_0 = 0$. Differentiating (2.6) with respect to X_i and setting equal to zero yields

$$\begin{aligned} cG(X_{i+1} - X_i) + v\int_0^{X_{i+q}-X_i} G(s)ds \\ = \int_0^{X_i - X_{i-1}} f(X_i - t)(vG(t) - cg(t))dt \,/\, f(X_i) \end{aligned} \tag{2.7}$$

where $G(s) = \int_0^{\infty} g(y)dy$. Setting $\varepsilon_i = X_{i+1} - X_i$, we get

$$cG(\varepsilon_i) + v\int_0^{\varepsilon_i} G(s)ds = \int_0^{\varepsilon_{i-1}} f(X_i - t)(vG(t) - cg(t))dt \,/\, f(X_i). \tag{2.8}$$

By Assuming a suitable value of X_1 one can compute the inspection schedule $X = (X_1, X_2, \ldots, X_n, \ldots)$ which satisfies the necessary condition of optimality by using (2.7) and (2.8).

The researches that have been done are first to recognize the trade off between costs of examination and losses due to late detection (even though sometimes it is hard to quantity the value of human life, but this is not the focus of our research here). Then some statistical models are built to link the basic elements that are involved in screening, for example, nature history of the disease, type of screening tests, screening times, treatments that follow a positive result. Finally a solution is derived based on the various assumption of deterioration and failure distribution.

2.3.3. Literature Review On Applications of CBM

CBM and the associated inspection and monitoring policies have been the subject of considerable research interest in recent years. In this section two papers are reviewed, one is by Barbera, Shneider and Kelle[1996]. In their paper, dynamic programming formulation is used to find the threshold condition for which it is optimal to initiate a preventive maintenance action. Another paper is by Christer and Wang. This paper addresses the problem of condition monitoring of a component that has a measure of wear available. Wear accumulates over time and monitoring inspections are performed at chosen times to monitor and measure the cumulative wear. If past measurements of wear are available up to the present, and the component is still functioning, the decision problem is to choose an appropriate time for the next inspection based upon the condition information obtained to date.

(1) **A Condition Based Maintenance Model with Exponential Failures and Fixed Inspection Intervals** (1996) by Barbera, Shneider and Kelle

At the beginning of equidistant time intervals, a unit is inspected, and it is assumed that the condition of the unit can be described by a quantity, X_t. The measurement is taken on a continuous scale. Time to failures follows a nonhomogeneous Poisson process, and the failure rate is an increasing function, $\lambda(X_t)$ of the variable X_t. The deterioration, Y_t, occurring during a period, is an independent and identically distributed non-negative random variable. Each period a decision is made to initiate a preventive maintenance action or to leave the unit alone. For each preventive maintenance action a fixed cost, K, is charged. If the unit fails a cost r occurs. The cost K

is strictly than the cost r. After a preventive maintenance action or failure (followed by a repair), the condition of the unit is restored to the initial value X_0 which is fixed and not a decision parameter. When no failure occurs during period t, the measurement of X_{t+1} at the beginning of period $t+1$, is given by

$$X_{t+1} = X_t + Y_t\,. \tag{2.9}$$

The probability that the unit will not fail by the end of time period t is given by

$$e^{-\lambda(X_t+Y_t)T}\,. \tag{2.10}$$

Note that this is identical to the probability that the time between failures is greater than T. The cost of failure per inspection period, given that the amount of deterioration at the beginning of period t was X_t, is the product of the cost of repair and the probability of failure during period t:

$$r[1-e^{-\lambda(X_t+Y_t)T}]. \tag{2.11}$$

The conditional expected cost of failure, H(X_t), given X_t, is found by integrating the conditional expression (2.11) with respect to the deterioration density function, $f(y)$:

$$H(Xt) = \int_0^\infty r[1-e^{-\lambda(X_t+Y_t)T}]f(y)dy. \tag{2.12}$$

After the preventative maintenance action the condition X_t will be returned to the initial state X_t and thus using the decision variable

$$\delta(X_t) = \begin{cases} 0 \text{ if no maintenanceaction is initiated} \\ 1 \text{ if a maintenance action is initiated} \end{cases}$$

the condition can be described by the variable X^*:

$$X_t^* = X_t - [X_t - X_0]\delta(X_t).$$

To find the threshold condition (X_t) for which it is optimal to initiate a preventive maintenance action, the dynamic programming formulation is used.

(2) A Simple Condition Monitoring Model for A Direct Monitoring Process

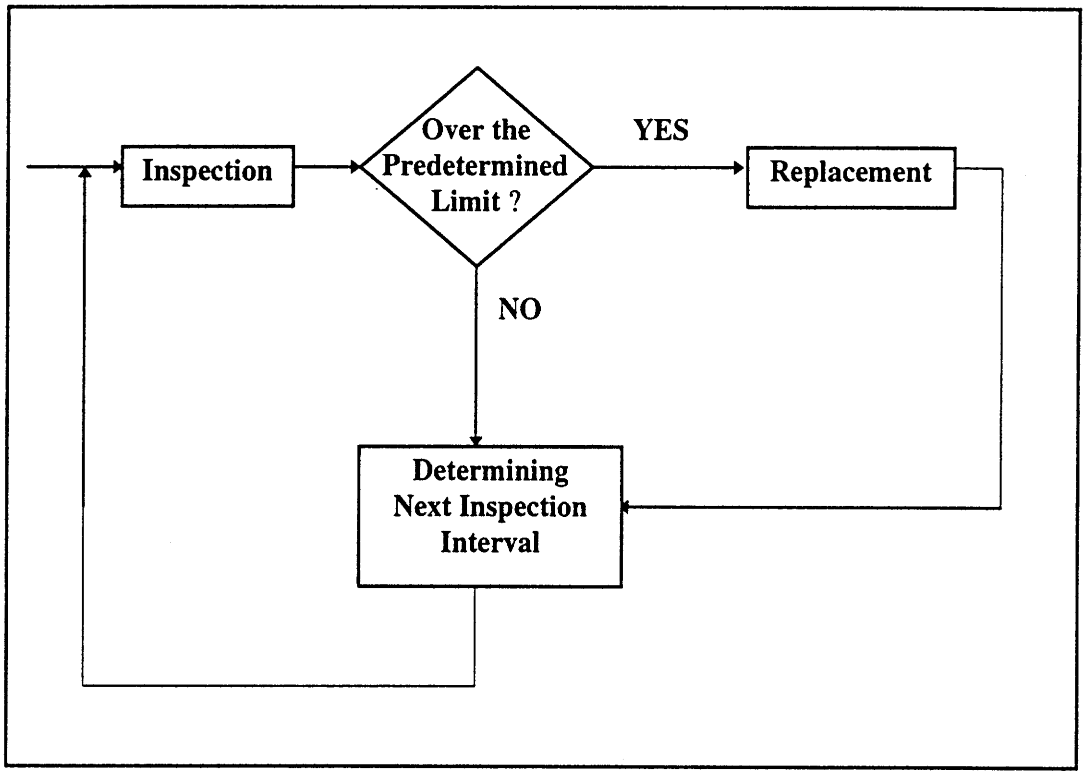
(1995) by Christer and Wang

The modeling objective is to decide at the current inspection t_n, assuming the component is still active at t_n, the next inspection time t_{n+1} based upon the condition information obtained at the past inspection times up to tn. Inspection point t_{n+1} is selected to optimize the expected cost per unit time over the period (t_n, t_{n+1}), that is, from the current inspection to the next scheduled inspection time.

The mathematical formulation is very similar to others we have reviewed, the new content brought by Christer and Wang is that, deterioration distribution is no longer to be assumed to be some well known and convenient statistical distribution, such as Poison. It will be derived based on the past inspection record. It is closer to reality.

From the above literature review, a typical CBM procedure can be summarized in a diagram in figure 2.1. CBM is carried out first by performing an inspection on the maintained assets, then the asset condition is compared with the predetermined limit, if it is over the limit, the asset is going to be replaced with a new one (sometimes a rebuilt one) and the interval of next inspection is determined, otherwise the asset remains in service and the interval of next inspection is determined. As we can see the CBM procedure is a loop and goes on and on. Normally it is assumed that the true condition of asset can obtained from the inspection (1) directly; (2) with 100 percent accuracy. For the second assumption, we just had a discussion of sensitivity and specificity in the last section. As the first assumption concerned, it sometimes may not be true. For example, in the case of freight car trucks, the internal condition of truck can not be inspected directly due to the nature of rail car structure, in this case, we have to develop some statistical models to estimate internal conditions by inspecting external components of freight car truck. This issue is going to be discussed in detail in next chapter.

Figure 2.2 CBM Procedure



Chapter 3

Inspection Approach to Support the Application of CBM in Freight Car Trucks

Freight car trucks are an important component of rail vehicles, affecting the dynamic performance in ways that can have economic impacts on the track, vehicle and lading [Guins and Hargrove, 1994], and present a useful example of many of the problems associated with developing and implementing an effective CBM program.

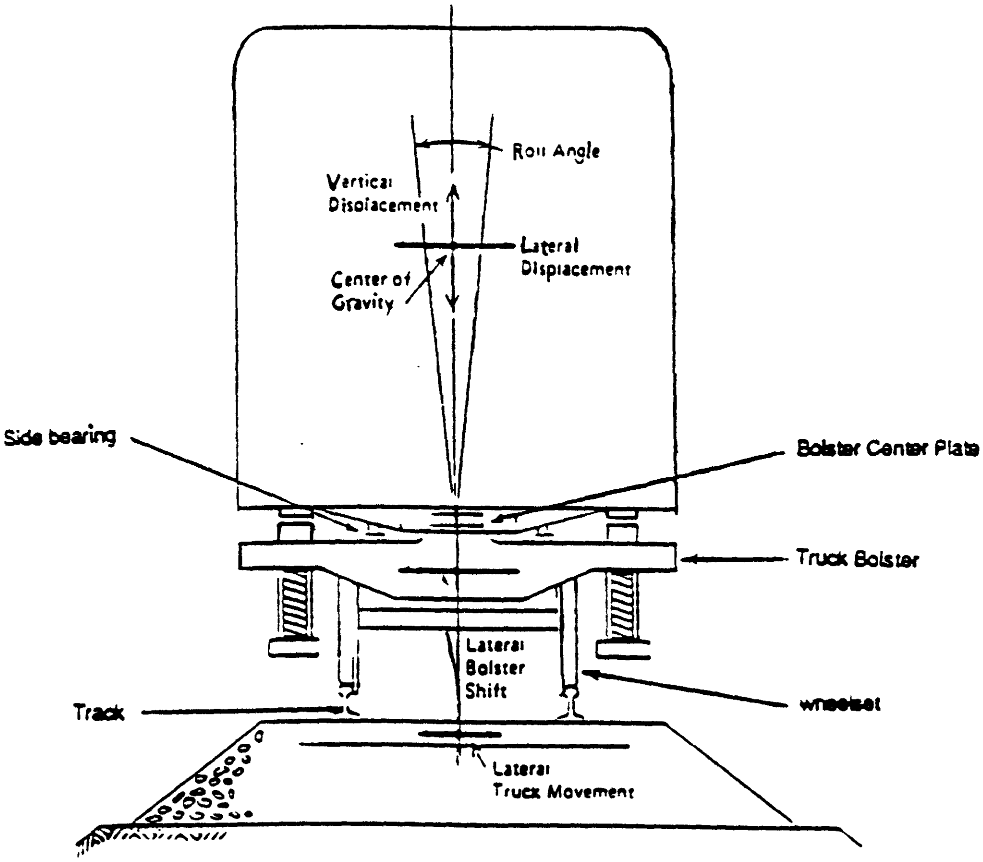
In this chapter, first, the basic structure of three-piece freight car truck is reviewed. This is followed by a discussion of external and internal inspection of freight car trucks. Finally, inspection approaches to support CBM is presented.

3.1. Three - Piece Freight Car Truck and Inspection

3.1.1. Overview

From an engineering point of view, the entire subject of railway system can be thought as the interaction between train and track [cf. Hay 1982], or train-track system. A train-track system is comprised of three parts, the car body, the truck and the track, as shown in figure 3.1.

Freight car trucks provide the means for both support of the car body and the mobility of the freight car itself via steel wheels on steel rails. Four-wheel, three-piece swivel trucks are the standard for American railway passenger cars and conventional freight cars (cf. Freight Car and Caboose Trucks, 1980). A three-piece freight car truck is



Source: *Railroad Engineering*, W. Hay, 1982.

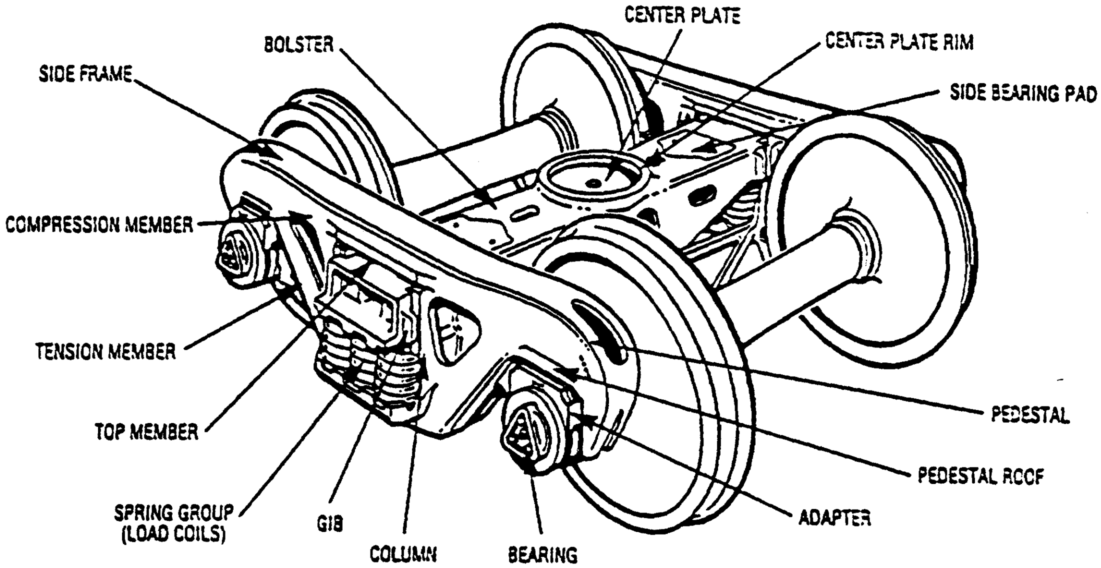
Figure 3.1. Train-Track System

characterized by three types of parts: one truck bolster, two side frames and two wheelsets (Shown in figure 3.2, 3.3, and 3.4).

When the train moves, shock force and friction will happen to the car body and truck. To reduce the shock, a suspension system is designed and implemented for all types of car trucks. The system includes groups of springs carrying the load, a spring-loaded friction shoe and in some case hydraulic shock absorbers. The friction shoes fits in the bolster friction pocket (shown in figure 3.5 and 3.6).

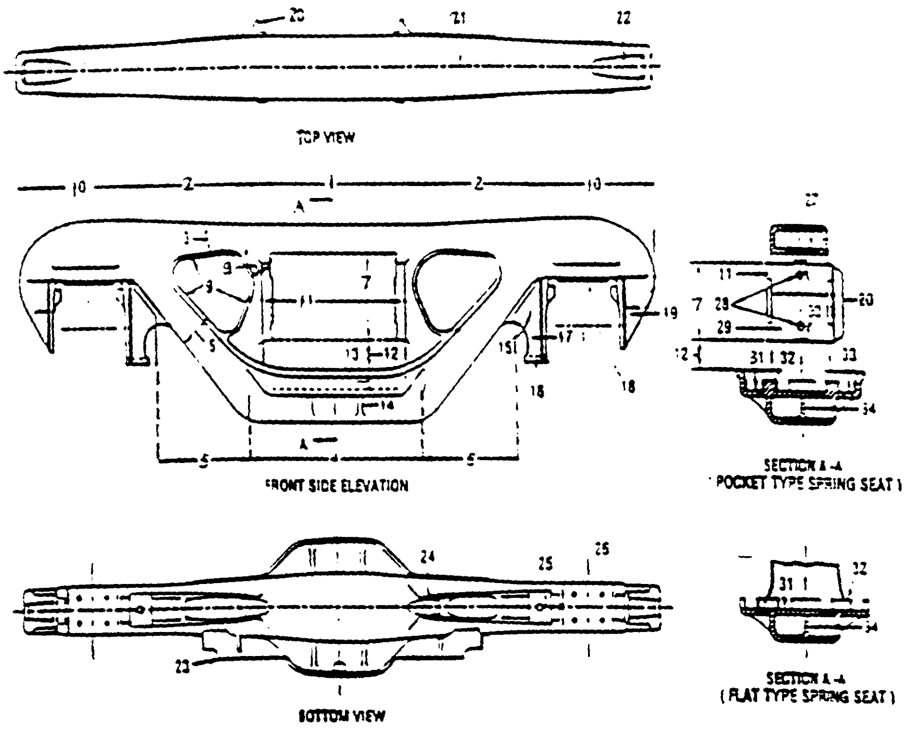
To dampen undesirable motions including vertical, lateral, longitudinal, rotational or any combination of such movements, several built-in mechanical friction liners, or plates, are designed and equipped on the freight car truck. Three types of liners are important in the later discussion of external condition and measurement, i.e. column wear liner, pocket wear liner and roof pedestal liner (shown in figure 3.5 and 3.6). The column wear liner is located between the inner side wall of the column and the outer side of the friction shoe. When the bolster moves up and down, the outer side of the friction shoes wears with the column wear liner instead of the inner wall of the column. The pocket wear liner is the liner located between the bolster pocket slope and the friction shoe. The roof pedestal liner is liner located between roof pedestal bearing adapter and truck sideframe. More detailed description about these two liners is given in the following chapters.

The bolster center plate not only functions as a pivot for the car body, but also carries the entire car body and loading weight into the truck structure. Although only a small rotating motion is sufficient in the center plate to permit trucks to negotiate even the sharpest curves, much concern is given to the plate's inner surface. Currently, the



Source: *ASF Maintenance and Repair Manual. Super Service Ride Control and Ride Control Trucks*. 1994.

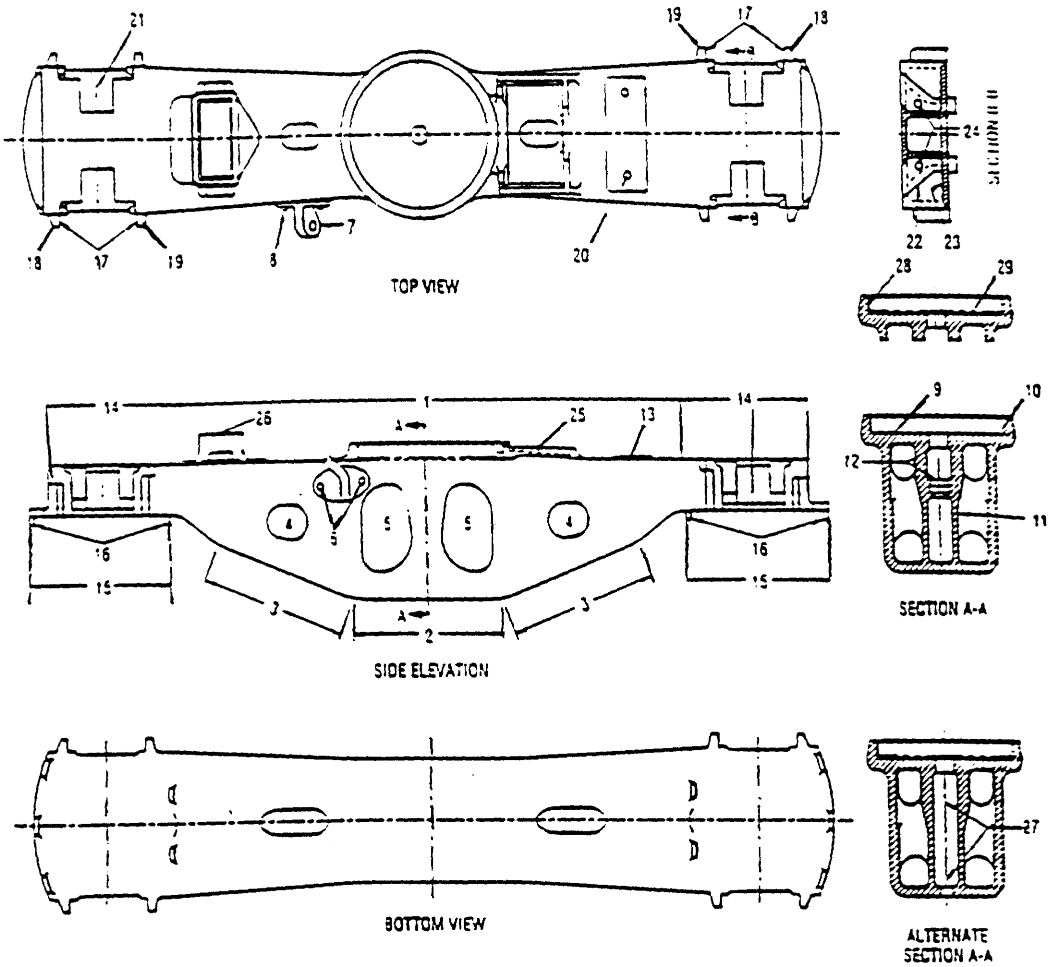
Figure 3.2 Three-piece Freight Car Truck



1. Top Member Center
2. Compression Members
3. Compression Member Flanges
4. Bottom Center
5. Diagonal Tension
6. Tension Member Flanges
7. Columns
8. Column Flanges
9. Windows
10. Top Ends
11. Inner Sides of Column
12. Lower Bolster Opening
13. Spring Seat Flanges
14. Spring Seat Ribs
15. Journal Bracket Flanges
16. Retainer Key Slot
17. Inner Pedestal Legs
18. Pedestal Roof Wear Liner
19. Outer Pedestal Legs
20. Bolster Anti-Rotation Lugs
21. Parting Line-Top Member
22. Top End Openings
23. Unit Brackets
24. Bottom Center Drain Holes
25. Parting Line-Bottom Member
26. Pedestal Roof Wear Liner Bosses
27. Top Member Bridge
28. Wear Plate Retainer Holes
29. Column Face
30. Column Wear Liner
31. Spring Seat
32. Spring Seat Bosses or Lugs
33. Spring Seat Drain Holes
34. Bottom Center Rib

Source: *ASF Maintenance and Repair Manual. Super Service Ride Control and Ride Control Trucks*, 1994.

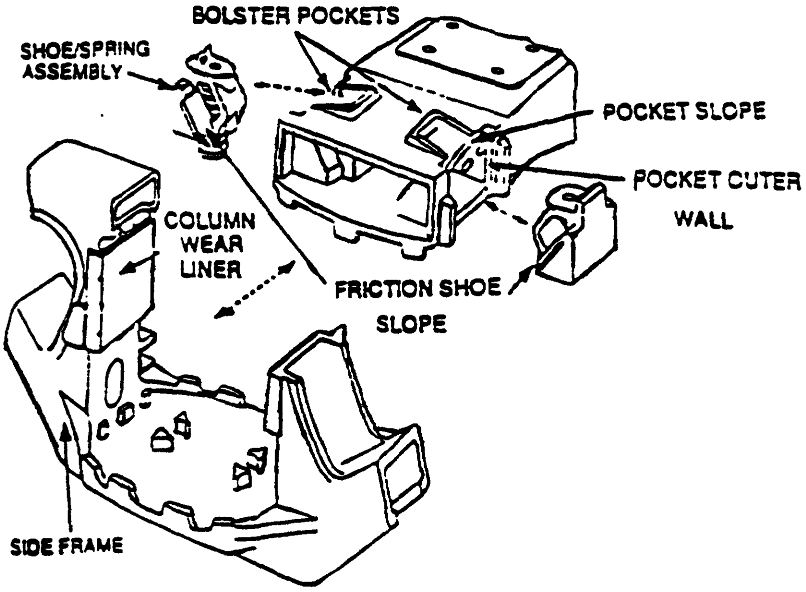
Figure 3.3 Side Frame



1. Top or Compression Member
2. Bottom Center Member
3. Diagonal Tension Member
4. Side Wall Lightener Holes
5. Brake Rod Holes
6. Dead Lever Lug Retainer Holes
7. Dead Lever Lug
8. Dead Lever Lug Rivets or Bolts
9. Center Plate Inner Surface
10. Center Plate Rim
11. Center Post
12. King Pin Well
13. Side Bearing Pads
14. Ends
15. Spring Seats
16. Spring Seat Lugs
17. Columns
18. Outer Column Guides-Gibs
19. Inner Column Guides-Gibs
20. Side Bearing Rivet or Bolt Holes
21. Friction Pockets
22. Friction Shoe Surface
23. Ride Control Spring Seats
24. Friction Shoe Retaining Pin Openings
25. C-Pep Pocket
26. Side Bearing Pocket
27. Locking Center Pin Opening
28. Center Plate Vertical Wear Liner
29. Center Plate Horizontal Wear Liner

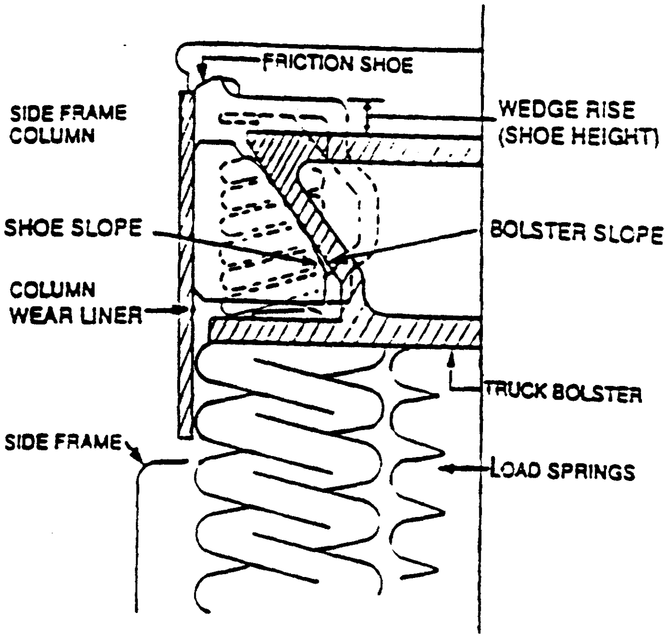
Source: *ASF Maintenance and Repair Manual, Super Service Ride Control and Ride Control Trucks*, 1994.

Figure 3.4 Bolster



Source: *Technical Papers. 1990 ASME/IEEE Joint Railroad Conference.*

Figure 3.5 Suspension System



Source: *Technical Papers. 1990 ASME/IEEE Joint Railroad Conference.*

Figure 3.6 Wear Surfaces and Liners around Friction Shoe

center plates for freight cars consist of casted inner surfaces covered by two abrasion resistant elastomeric center plate liner, i.e. bolster vertical wear liner and bolster horizontal wear liner. These two liners are also described in more detail in the following chapter.

3.1.2. External Condition and Inspection

External condition refers to the condition of external parts that can be inspected without taking the car body off. The purpose of inspection on freight car truck is to prevent potential failures. There are several levels of failures caused by different type of truck defect. If some components of truck, such as truck spring, side bearing, pedestal thrust lugs, and friction wear plate, have excessive wear, then rail car may still be able to move, but will not be as smooth as it should be. This will cause high operating cost, damage to the freight. Thus such car has to be take out off service, normally classified as “bad order." On the other hand, if some of major components of truck, such as side frame of bolster, has a serious crack or is broken, then it may cause some serious consequences, such as derailment.

There are two types of external inspection. One type of external inspections of freight car trucks are performed in train yards upon train arrival or before train departure. Another type of external inspections are performed in the car shop after cars are taken to the car shop for “bad order” due to various damages.

When inspection is performed in the railroad yard, inspectors inspect side frame, wheels, and suspension system. These inspections are normally a combination of visual inspection of surface of truck and gages' measurement of certain components. A defective freight car will be marked as a bad order and will be taken out of service.

According to AAR Railroad Freight Car Safety Standard, Rule 215.119, A railroad may not place or continue in service, *if the car has -*

(a) *A side frame or bolster that -*

  (1) *Is broken, or;*

  (2) *Has a crack of 11/4" of an inch or more in the transverse direction on a tension member.*

(b) Spring assembly solid or snubber broken or missing.

(c) *A side bearing in any of the following conditions:*

  (1) *Part of the side bearing assembly is missing or broken;*

  (2) *The bearings at one end of the car, both sides, are in contact with the body bolster (except by design);*

  (3) *The bearings at one end of the car have a total clearance from the body bolster of more than 3/4 of inch;*

(d) *Truck springs*

  (1) *That do not maintain travel or load;*

  (2) *That are compressed solid; or*

  (3) *More than one outer spring of which is broken, or missing, in any spring cluster;*

A side frame or bolster can be damaged by coming in contact with an obstruction or by a rigid truck (often caused by no side motion due to defective center plate, broken or missing springs.

Once a car is placed as a bad order for its defective truck, it will be taken into a car shop, further inspection for external parts are performed. According to AAR Specification, inspect, gage and repair side frames as follows:

A. *Column Guides*

  1. *Inspect column guides for wear and gouges. Nominal column width is 7 1/2", if column is worn in excess of 1/8", side frame must be reconditioned per AAR Specification M-214.*
  2. *Inspection rotation stops on side frame inner column. Nominal distance between rotation stops in 17 3/16", if this dimension exceeds 17 33/8", side frame must be reconditioned per AAR Specification, M-214.*

B. *Pedestal Thrust Lugs*

  1. *Gage longitudinal thrust lug wear according to AAR S-378. Nominal distance between thrust lugs is 7 1/4", if longitudinal distance between thrust lugs is not more than 7 1/2" and wear does not effect wheel base, i.e. wheel base matches the buttons as originally manufactured, no repair is necessary. If repair is necessary for either of the above reasons, side frame must be reconditioned per AAR Specification M-214.*
  2. *Check width of pedestal thrust lugs. Nominal width is 3 1/2", if width is reduced below 3 33/8", side frame must be reconditioned per AAR Specification M-214.*

C. *Friction Wear Plates*

1. *Measure distance between side frame and column wear plates. Nominal dimension is 14 1/2", if distance between wear plates exceeds 14 11/16" at any point, or if wear plate is cracked or broken (other than cracked retaining welds which may be rewelded) both column wear plates must be removed and new wear plates applied using mechanical fasteners per AAR Specification S-320 or S-3003.*

D. *Pedestal Roof*

1. *Remove any existing roof liners and prepare pedestal roof for application of "Transdyne" roof liners according to the manufacturers instructions.*

3.1.3. Internal Condition and Inspection

We have discussed train-track system in which truck bolster contact with car body through the truck center plate bowl. As shown in figure 3.1, the condition on the central truck bolster areas cannot be inspected directly without taking the car body off. Therefore it is referred as internal condition in this study. The related parts are referred to as internal parts. Among all the internal parts of a truck, the center plate bowl is the most vulnerable part and its condition affects the quality of the movement of car body directly.

As we described in the last section, further external inspection is performed once a car is dispatched to a car shop for bad order. After the external inspection, a responsible car shop engineer will decide whether to disassemble the car (lifting the car body off the truck) and to inspect internal parts. If the engineer suspects that there may be some defects in the center plate bowls based on the external conditions, then he/she will decide to do so.

The judgment is mostly based on engineers experience and may be subject to two problems. One is the overestimation of the condition of wear of internal parts, and other is the underestimation. Each situation is associated with certain consequence and cost. If the wear condition for a truck is overestimated, then the truck will be disassembled even though the truck internal condition is still good. This will cause the cost associated with disassembling the truck, the cost for the loss of service time, or even the cost of market shares due to lack of car resource. On the other hand, if the case is underestimation, even though the internal condition of a truck is very poor, it will still be kept in the service, then the potential failure may happen, which is associated with certain cost. This is a critical issue when applying CBM to freight car trucks, which will lead to more study in next section.

In practice, there is no single measurement of center plate applied to determine the internal condition of truck. Instead, a combination of wear measurements of center plate liners is used. Once the car body is taken off the truck, inspectors are supposed to do the following according to American Association of Railroad (AAR) Specification M-214:

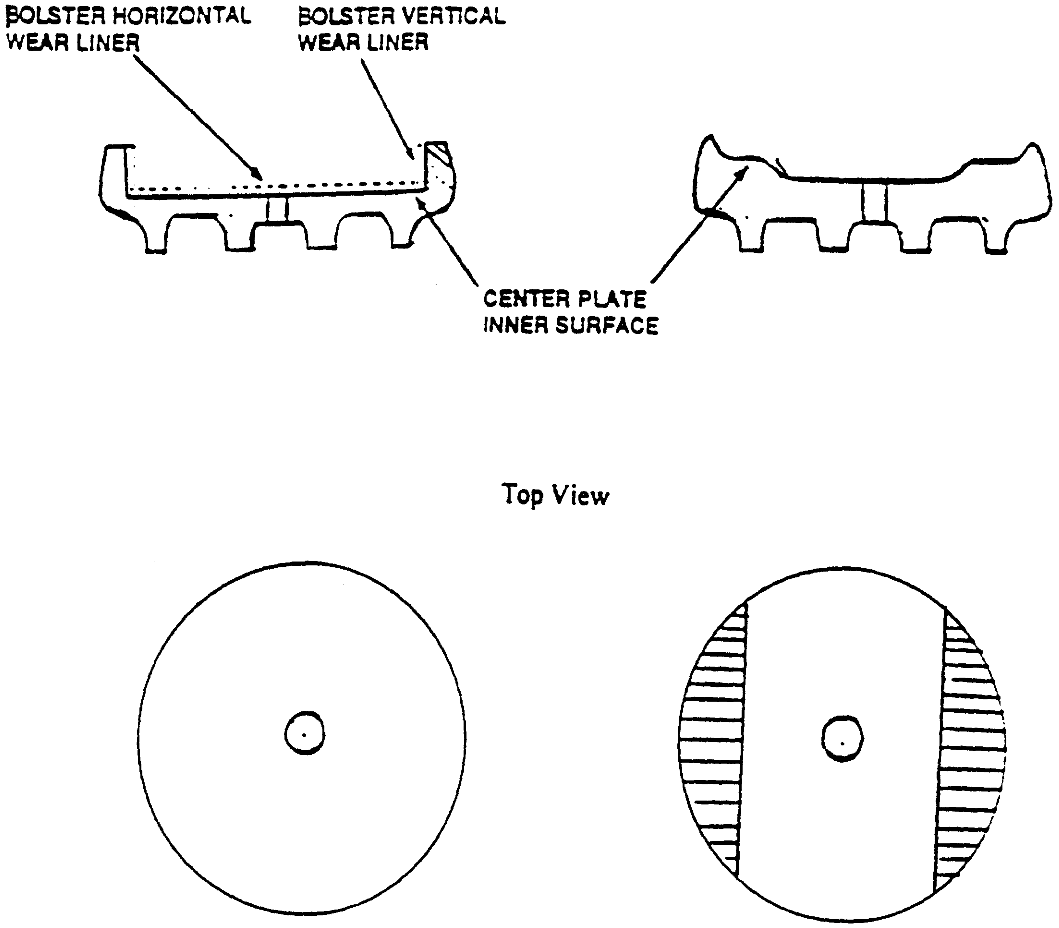
1. *Measure depth of center plate bowl. Nominal dimension is 1 1/8", if depth exceeds 1 11/32", bolster must be reconditioned per AAR specification M-214.*
2. *Measure diameter of center plate bowl, if bowl diameter exceeds 14 1/4" at any point, vertical wear liner must be replaced. Note that if bowl diameter exceeds 14*

58/8" at any point, entire bolster must be reconditioned per AAR Specification M-214.

In figure 3.7, both new and worn shapes of bolster center plate are illustrated.

Side Elevation

Top View



(i) the shape of new center plate

(ii) the shape of worn center plate

Figure 3.7 Bolster Center Plate

3.2. Inspection Approaches to Support CBM

As discussed in chapter 2 and also illustrated in figure 2.1, the starting point for CBM is the determination of the true condition. To apply CBM to rail car trucks, the true condition of truck internal parts, especially the condition of center plate bowl, is needed.

Unfortunately, the internal component is not accessible without taking car body off the truck. In practice, railroad car shop engineers tend to estimate the internal conditions of a truck based on some of external conditions and their experience, which is not very accurate. Chang [1995] has attempted to address this problem by applying two statistical forecasting techniques, discrete choice method and performance threshold method, to develop a more effective inspection approach.

It is necessary to describe the underlying rationale for this proposition, which is to predict the internal condition of rail car truck from the external condition. Since the three-piece freight car truck is a complex mechanical system, the performance and wear conditions of the different parts are likely to be interactive and integrative from one to another. Internal bolster is the only place taking all the weight of the car body and the freight loading, and all the forces are transmitted throughout the truck, especially the external area. Therefore, external conditions to some extent should be expected to reflect the overall performance of the internal bolster parts. This concept supports the predictive inspection approach for the internal bolster condition.

The idea is as follows. First, both data for internal condition and external condition are collected. Second some mathematical relations between internal and external condition are established by applying statistical data modeling techniques.

Finally, the internal condition of a car truck is predicted based on its external condition. The data could be collected in the railroad car shop where cars are maintained.

The author of this thesis has conducted further research in applying statistical modeling techniques to predict internal condition of a truck by inspecting its external components. In Chang's work, two types of statistical modeling techniques were analyzed and calibrated into the models, some data from a rail carrier was applied in those two models, but only moderate results were obtained. The two models were able to accurately predict the internal state of the truck approximately only 55-60% of the time. There were a number of reasons that were responsible for the results, which will be discussed in detail later, one of them was that data were not complete. In order to improve the modeling results, the author has reviewed the data with railroad managers from one of the major north American railroads. We also collected more data from the railroad car shop, and applied to undated versions of models.

In this section, first, statistical forecasting techniques are reviewed, then results from both previous work and author's continued research are presented.

3.2.1. Review of Statistical Forecasting Techniques

Two statistical forecasting methods are presented in Chang's research, i.e., discrete choice method and performance threshold method.

3.2.1.1. Discrete Choice Method

In discrete choice method, dependent variable has a value from a set of alternatives or choices, instead of continue value as in linear method. Discrete choice method seeks to find the link between the probabilities of dependent variable and independent variables.

Discrete choice method is rooted from random utility theory. Utility is the term used by economists to describe the level of satisfaction or happiness derived from the consumption or use of a good or service. According to classical consumer theory in microeconomic analysis, every consumer or user will choose the alternative or choice with the largest utility across the choice set. In random utility theory, the utility is considered to consist of two parts, first part is called systematic factor, and second part is called random factor. For systematic factor, there are two types of independent variables. One is the attributes of each alternative. In the case of transportation mode choice analysis for freight shippers, in which shippers select a particular mode from a set of alternatives or choices i.e., rail, truck, intermodel, delivery time (days), freight rate (dollar per unit), reliability (on time rate) and safety and damage (damage rate) of each mode are applied. The other one is the shipper's socioeconomic characteristics, e.g., the size of the shipper, the cost structure of the shipper and the nature of freight to be transported. The random part of a utility is account for all the factors that influence the decision of choice but are unobservable or unexplainable. A example of utility for transportation mode choice is [Ben-Akiva and Lerman, 1985],

$$\begin{aligned} u^1 &= \beta_0 + \beta_1 x_1^1 + \beta_2 x_2^1 + \beta_3 x_3^1 + \cdots + \beta_k x_k^1 + \varepsilon^1 = v^1 + \varepsilon^1, \\ u^2 &= \beta_0 + \beta_1 x_1^2 + \beta_2 x_2^2 + \beta_3 x_3^2 + \cdots + \beta_k x_k^2 + \varepsilon^2 = v^2 + \varepsilon^2, \\ u^3 &= \beta_0 + \beta_1 x_1^3 + \beta_2 x_2^3 + \beta_3 x_3^3 + \cdots + \beta_k x_k^3 + \varepsilon^3 = v^3 + \varepsilon^3, \end{aligned} \tag{3.1}$$

where:

- u^1,u^2 and u^3 are the utilities of the modes rail, truck and intermodal for the shipper respectively;
- $\beta_0, \beta_1, \beta_2, \beta_3, \ldots \beta_k$ are unknown parameters which are to be estimated by discrete choice models;
- $x_1^i, x_2^i, x_3^i, \ldots\ x_k^i$ (i=1,2,3) are the variables of the alternative's attributes and shipper's socioeconomic characteristics for each alternative i, e.g. x_1^1, x_2^1, x_3^1 are transit time of the three modes;
- v^1, v^2 and v^3 are the systematic components; and
- ε^1, ε^2 and ε^3 are the random terms for each alternative.

Because the utility of each alternative has a random term, any of them may have the highest utility, thus every alternative has some possibility to be chosen. In above case, the probability for a shipper to choose rail (mode 1) over truck (mode 2) or intermodal (mode 3) is,

$$Pr(mode\ 1) = Pr(\ u^1 \geq u^2\ and\ u^1 \geq u^3). \qquad (3.2)$$

More generally, alternative i would be chosen with the probability,

$$Pr(i) = Pr\ (u^i \geq u^j),\ for\ all\ j \neq i\ and\ i, j \in (1,2,3). \qquad (3.3)$$

In order to be able to calculate the probability for each mode, more concrete specification of the distribution of the random term must be made. The most frequently used specification is Gumbel distribution (Johnson and Kotz (1970) and Domencich and McFadden (1975)), which can be expressed as,

$$f(\varepsilon) = \mu e^{-\mu(\varepsilon-\eta)} \exp[-e^{-\mu(\varepsilon-\eta)}], \tag{3.4}$$

where μ and η are two parameters. If the random term is assumed Gumbel distribution, then the difference between random terms associated with two modes ε^i - ε^j is logistically distributed. That is why this method sometimes referred as logit model. Based on the assumption above, the probabilities of each alternative being chosen will have the following function form,

$$\begin{aligned}\Pr(i) &= \Pr(u^i \geq u^j) \text{ for all j} \neq \text{i} \\ &= \frac{e^{v^i}}{e^{v^1} + e^{v^2} + e^{v^3}} \\ &= \frac{e^{v^i}}{\sum_{j=1}^{3} e^{v^j}}\end{aligned} \tag{3.5}$$

In other words, the probability of alternative i being chosen is equal to the proportion of the exponential value of alternative i's utility to the summation of the exponential values of all the alternatives' utilities.

In the case of freight car truck, if we categorize the internal condition by the repairs done around center plate area, and define the internal condition with several states, e.g. “good”, “OK” and “bad”, according to some criterion about the repair work (for example, in Chang’s work, if the type of work being done to a truck is nothing or rewelding of bolster vertical wear liner(BVWL), then the internal condition of this truck is categorized to state “good”; if the BVWL is rewelded and the bolster horizontal wear liner(BHWL) is replaced, then the internal condition of this truck is categorized to state “bad”; if BVWL is replaced, then the internal condition of this truck is categorized to state “poor”. Then we can apply discrete choice method to predicting the internal condition of rail car truck from its external conditions. There are some analogous aspects between predicting freight car truck internal condition and the above freight mode choice example. Pre-defined states of internal bolster condition are considered as the alternative choices and the external measurements the independent variables. Similar to the concept “utility”, Chang used “tendency” in the freight car context. Then the tendencies for three internal states are defined as follows,

$$\begin{aligned} T^1 &= \alpha_0 + \alpha_1 x_1^1 + \alpha_2 x_2^1 + \alpha_3 x_3^1 + \cdots \alpha_k x_k^1 + \varepsilon^1 = d^1 + \varepsilon^1, \\ T^2 &= \alpha_0 + \alpha_1 x_1^2 + \alpha_2 x_2^2 + \alpha_3 x_3^2 + \cdots \alpha_k x_k^2 + \varepsilon^2 = d^2 + \varepsilon^2, \\ T^3 &= \alpha_0 + \alpha_1 x_1^3 + \alpha_2 x_2^3 + \alpha_3 x_3^3 + \cdots \alpha_k x_k^3 + \varepsilon^3 = d^3 + \varepsilon^3, \end{aligned} \tag{3.6}$$

where T^i are the tendencies of internal condition being in state i; x_k^i are the conditions of external components (i=1,2,3), d^1, d^2 and d^3 are systematic components of the tendencies, ε^1, ε^2 and ε^3 are random disturbances.

The probability being in state i is the probability that the tendency to be in state i is larger than the tendency to be in any other state j. This can be expressed as,

$$\begin{aligned}\Pr(i) &= \Pr(T^i \geq T^j) \text{ for all } j \neq i \\ &= \frac{e^{d^i}}{e^{d^1} + e^{d^2} + e^{d^3}} \\ &= \frac{e^{d^i}}{\sum_{j=1}^{3} e^{d^j}}\end{aligned} \tag{3.7}$$

Even though we have shown that there is similarity between the discrete choice analysis in the context of freight modes and freight car truck internal conditions, some differences still exist. One is that discrete choice model for freight modes is based on traditional consumer utility theory, a strong causal relationship is known to exist between utilities and the attributes of alternatives and the shipper's socioeconomic characteristics. On the other hand, it is clear that the external condition is not causal of the internal state, and the internal states, as defined, have somewhat of an arbitrary character. The internal states and external measurements are more likely to be different indices of the truck's overall performance and condition. Another difference is how the state(choice) is defined in two cases. Alternative shipping modes are absolutely discrete while internal condition is categorized into several states according to some essentially artificial criteria. This problem leads to the application of performance threshold method, which is to address this weakness.

3.2.1.2. Performance Threshold Method

As discussed earlier, the reason of to predict internal condition is to help railroad car shop manager make an effective decision on whether the car body is taken off and then whether the center plate liners is rewelded or replaced. The internal condition could be ideally a continuous measure, but what is needed is a series of ordinal states that corresponding varied decisions discussed above.

In 1975, Mckelvey and Zavoina proposed a statistical method called ordinal probit method in general econometric terminology, to apply in the situations that in many statistical inference applications, the dependent variable, which is otherwise essentially continuous, falls in some ordinal levels of intervals. The freight car internal condition prediction may be considered as a case of this. In Chang's work, this method is called performance threshold method due to its application to the machinery inspection context. To be consistent, it is continuously referred as performance threshold method throughout this thesis.

With the same assumption of discrete choice model that the internal truck condition can be indicated by its external condition, the performance function consists of two parts, i.e., a systematic and a random part. The performance function can be shown as follows [Chang 1995],

$$P_n = \sum_{k=1}^{K} \beta_k x_{kn} + \mu_n, \tag{3.8}$$

where P_n is the performance of internal area of truck n; x_{kn} is the *k*th external measurement variable, $k = 1, 2 \ldots K$; βk is the parameter for the external variable x_{kn}, $k =$

1, 2 ... K; and μ_n is the random disturbance term for the underlying performance function of internal area of truck *n*.

Because the internal condition, or performance, can not be observed, the observable repair data are assumed to be the indicators of the underlying performance. The observable repair data then is categorized to one of a series set of ordinal states which have two predefined contiguous thresholds. If *M* ordinal states are defined and hence *M* thresholds levels are identified, then there will be *M-1* thresholds. This can be shown as follows [Chang 1995],

$$-\infty = t_0 < t_1 < t_2 < \cdots < t_{M-1} < t_M = +\infty, \tag{3.9}$$

where $t_1, t_2 \ldots t_{M-1}$ are the thresholds for the performance; and

$$C_n \in S_m \Leftrightarrow t_{m-1} \le P_n \le t_m, \tag{3.10}$$

where C_n is the observed internal truck state for truck *n*; S_m is the ordinal state *m*; t_{m-1} is the lower bound threshold for the performance corresponding to the ordinal state *m*; and t_m is the upper bound threshold for the performance corresponding to the ordinal state *m*.

A binary variable can be used to indicate whether a truck performance belongs to one of the ordinal states, sometimes it is called dummy variable, as follows,

$$C_{nm} = \begin{cases} 1 \text{ if } C_n \in S_m \\ 0 \text{ otherwise} \end{cases}, \tag{3.11}$$

which says that dummy variable C_{nm} will equal *1* if the truck *n*'s internal condition is *n* state *m*, *0* otherwise.

The following can be summarized and derived from above equations,

$$\begin{aligned} C_{nm} = 1 &\Leftrightarrow C_n \in S_m \Leftrightarrow t_{m-1} \le P_n \le t_m \\ &\Leftrightarrow t_{m-1} \le \sum_{k=1}^{K} \beta_k x_{kn} + \mu \le t_m \\ &\Leftrightarrow t_{m-1} - \sum_{k=1}^{K} \beta_k x_{kn} < \mu < t_m - \sum_{k=1}^{K} \beta_k x_{kn}. \end{aligned} \tag{3.12}$$

$$\begin{aligned} \Pr(C_{nm} = 1) &= \Pr(t_{m-1} - \sum_{k=1}^{K} \beta_k x_{kn} < \mu < t_m - \sum_{k=1}^{K} \beta_k x_{kn}) \\ &= \Pr\left(\frac{t_{m-1} - \sum_{k=1}^{K} \beta_k x_{kn}}{\sigma} < \frac{\mu}{\sigma} < \frac{t_m - \sum_{k=1}^{K} \beta_k x_{kn}}{\sigma} \right) \\ &= \Phi\left(\frac{t_{m-1} - \sum_{k=1}^{K} \beta_k x_{kn}}{\sigma} \right) - \Phi\left(\frac{t_m - \sum_{k=1}^{K} \beta_k x_{kn}}{\sigma} \right), \end{aligned} \tag{3.13}$$

where Φ() represents the cumulative standard normal distribution function. Assuming further, without loss of generality, that $t_1 = 0$ and $\sigma=1$, the final model is given by,

$$\Pr(C_{nm} = 1) = \Phi(t_m - \sum_{k=1}^{K} \beta_k x_{kn}) - \Phi(t_{m-1} - \sum_{k=1}^{K} \beta_k x_{kn}), \tag{3.14}$$

if the ordinal state *m* is an interval defined by two thresholds, t_{m-1} and t_m, then equation 3.14 shows that the probability of the internal condition of truck *n* being in state *m* is equal to the difference of two standard normal cumulative functions valued at two points. These two points are the differences between the upper threshold of the interval *m* and the systematic part of the performance function and the lower threshold of the interval *m* and the systematic part of the performance function.

In equation 3.14, $t_1, t_2, t_3 \ldots t_m$ are thresholds. In the case of freight car truck, two thresholds are needed to define three ordinal states, i.e., "good", "OK", "bad". $x_{1n}, x_{2n}, x_{3n} \ldots x_{kn}$ are external measurements for truck *n*. $\beta_1, \beta_2, \beta_3 \ldots \beta_k$, are unknown parameters, which can be estimated with maximum likelihood estimation method.

3.2.2. Previous Data Modeling

In Chang's research, discrete choice method and performance threshold method were applied to the data collected from the inspection and repair reports provided by a Canadian private car owner, Sultran Ltd. The reports were generated in the car shop where varied repair/replacement work are being done to the car. Cars were pulled into car shop for varied reasons, i.e., broken car body, bad truck(external components), bad coupler.

Total 222 trucks, two trucks for each of 111 cars, were included. Twelve external measurements of three types of external components which were believed to be effective indicators for internal condition were selected from the reports, i.e., "pocket wear plate", "pocket outer wall" and "roof pedestal liner", two for each of left and right side of the truck. In the report, the conditions of the pocket wear plate and roof pedestal liners were measured with various qualitative and descriptive judgments such as “both OK”, “both worn out”, “one good and one worn”, etc. The wear on the pocket outer wall was measured by the depth of the wear with one unit as 1/16 inch. The states of internal condition for discrete choice models and performance threshold models were defined based on the types of work being done to the car.

As result of these two models from this Sultran data, both of them were able to accurately predict the internal state of the truck approximately only 55-60% of the time. Part of the low prediction rate may blame to the poor quality of data. As mentioned in last paragraph, two of the three external parts were measured in qualitative terms, such as “OK” or “worn”, which were not particularly fitting in the model underlying assumption.

One thing worth noting is that, although the numerical results of the discrete choice method and performance threshold method are essentially similar, the performance threshold model is clearly preferable in terms of the underlying behavioral assumptions. This would be evidenced by the higher statistical indices, i.e., goodness of fit, *t*-statistics, in the performance method.

3.2.3. Continuous Data Modeling

As continuous effort to improve the inspection and prediction method, first more complete data were collected and more external measurements were added during author’s field visit and study in a major north American railroad car shop. Second the model structure was enhanced. Throughout this thesis, Chang’s work is referred as first round modeling and author’s work is referred as second round modeling.

When we reviewed the modeling result from Chang's work, we suspected that incomplete data, such as the measurements for two external parts in qualitative term, may be blamed for poor prediction rate, but also more external measurements may be needed for effective prediction of internal condition. As a result, in the new data collected from the field study, all external measurements were in quantitative term, and three new external measurements were recommended by the car shop engineers. The first new external measurement, wedge rise (shoe height), is a very important measurement of the suspension system area's wear, which was mentioned in Chang's study, but wasn't available in the original data reports. The second and third of new external measurements were gib spacing and column wear liner. All the external measurements (independent variable) are listed in table 3.1.

Table 3.1 External Measurement

Definition	**Description**
1. Pocket Wear Liner	Located between bolster slope pocket and slope surface of friction shoe.
2. Roof Pedestal Liner	Located between side frame pedestal and wheel adapter.
3. Pocket Outer Wall Wear	Surface between corners of friction shoes and slope pockets.
4. Wedge Rise	Height between top of shoes and top of the bolster.
5. Gib Spacing	Distance between bolster gibs. Nominal dimension = 8 1/4".
6. Column Wear Liner	Distance between side frame and column wear plates. Nominal dimension = 14 1/2".

In second round modeling, only performance threshold method was applied, and new indices was used for internal condition. Recall that in the first round modeling, although the correct prediction rates for discrete choice method and performance threshold method were almost same, but performance threshold method showed some advantages in terms of goodness of fit and *t*-statistics, which indicate how the data fit the model, this is because performance threshold method treats the trucks' internal conditions (alternative or choice) as ordinal alternatives while discrete choice method treats the trucks' internal conditions as discrete alternatives. For this reason, in second round modeling. Only performance threshold method was applied.

In terms of data collection, 30 trucks (15 cars) were collected from the trip study. At about the same time, another set of 80 inspection reports (80 trucks, 40 cars) was received from Sultran with the additional external measurements.

The second round modeling produced much promising results. Data from 50 trucks were used to collaborate the model and rest 60 trucks data were tested for this model. Correct prediction rate was improved to 75 - 80%.

Recall in chapter 2 we have discussed sensitivity and specificity along with false positive rate and false alarm rate for an inspection. In the context of inspection of truck, sensitivity can be used to describe the ability of an inspection to detect the bad trucks (internal condition), and specificity is the ability to detect the good trucks (internal condition). In other words, sensitivity and specificity indicate the probability that the inspection method indicates a truck in bad (good) condition, given that the truck's internal condition indeed is bad (good). "Positive" is a term used in medical examination, if a test for a disease is positive, it means the disease is not present. False positive rate is the underestimation rate of an inspection, and false alarm rate is the overestimation rate of an inspection. These four parameters were calculated for the first round and second round model and the results are listed in table 3.2. It shows the improvement of second round model over first round model.

For second round model, it can detect the trucks with bad internal condition very effectively (sensitivity = 95%), but tend to overlook the trucks with good internal conditions (false alarm rate = 72%). This problem could be traced back to the data collection and structure of data. Recall that data were collected at railroad car shop, where cars were pulled in for varied problems, and defective truck is one of the major problems, this leaded to that major portion of data collected were for cars with defective trucks. When maximum likelihood method was used to estimate the model, it tends to "favor" bad trucks. In the future, this problem would be solved by using more balanced data.

Table 3.2 (a) Calculation of Sensitivity and Specificity
for First Round Model

<table>
<tr><th></th><th>Bad (true condition)</th><th>Good (true condition)</th></tr>
<tr><td>Bad (predicted)</td><td>32</td><td>16</td></tr>
<tr><td>Good (predicted)</td><td>12</td><td>8</td></tr>
<tr><td>Total</td><td>44</td><td>24</td></tr>
<tr><td colspan="3">Sensitivity = 73% Specificity = 33%
False positive rate = 27% False alarm rate = 67%
Correct prediction rate = 59%</td></tr>
</table>

Table 3.2 (b) Calculation of Sensitivity and Specificity
for Second Round Model

<table>
<tr><th></th><th>Bad (true condition)</th><th>Good (true condition)</th></tr>
<tr><td>Bad (predicted)</td><td>39</td><td>12</td></tr>
<tr><td>Good (predicted)</td><td>3</td><td>6</td></tr>
<tr><td>Total</td><td>42</td><td>18</td></tr>
<tr><td colspan="3">Sensitivity = 93% Specificity = 33%
False positive rate = 7% False alarm rate = 67%
Correct prediction rate = 75%</td></tr>
</table>

Overall, the result from this second round model was very encouraging. With 70-80% prediction rate and 93% sensitivity, it can be applied in the CBM inspection procedure, with some caution and adjustment due to its high false alarm rate.

Chapter 4

An Economic Model of CBM

4.1. Introduction

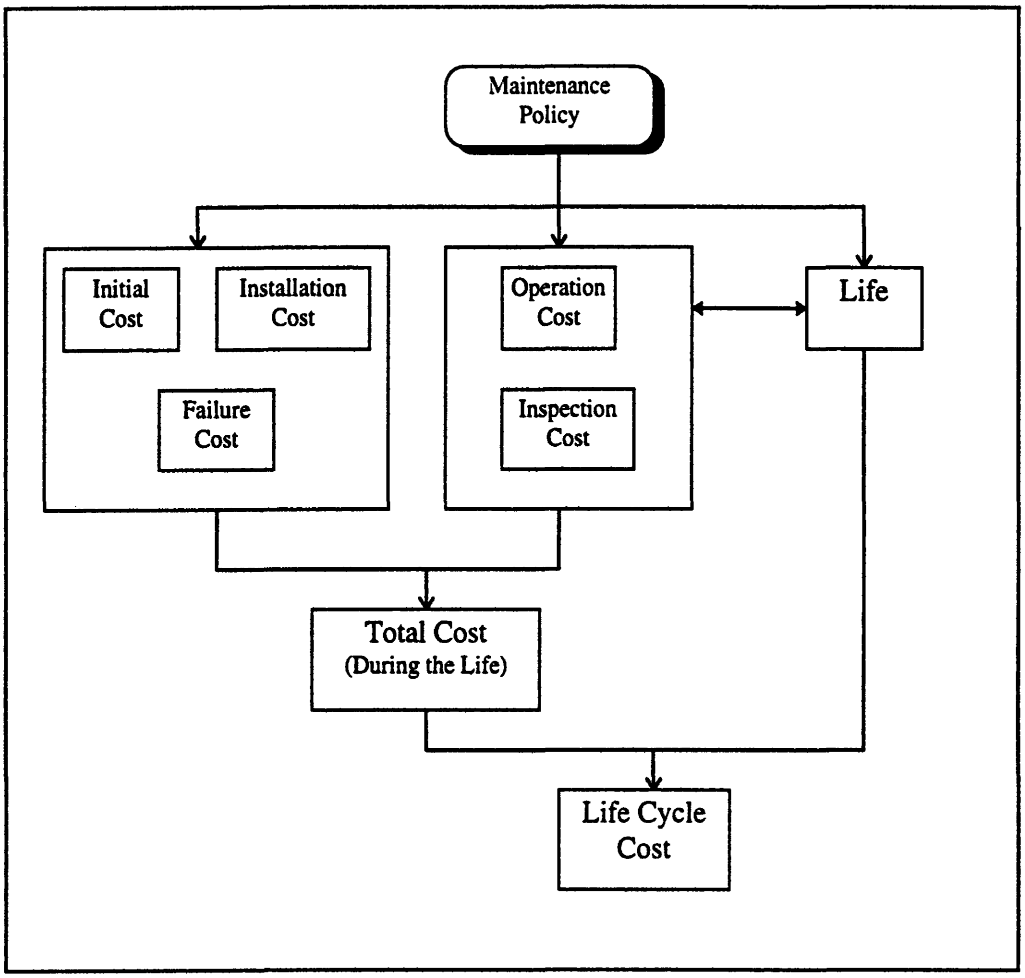
In chapter 2 we indicated that CBM, if implemented properly, could result in lower life cycle cost than alternative maintenance policies, i.e., periodical replacement and replace upon failure. This section presents an economic model to illustrate how the maintenance policies effect the life cycle cost of freight car truck and how CBM can be implemented for freight car truck maintenance with the incorporation of the inspection approach that was discussed in last section.

Recall that life cycle cost can be calculated by using equation 2.1.

$$LCC = \frac{\text{init\_cost} + \text{op\_cost} + \text{insp\_cost} + \text{inst\_cost} + \text{fail\_cost}}{\text{life}}$$

In this equation, some components are very straightforward to calculate, such as initial cost, maintenance cost; some components only apply to certain policies, such as failure cost for replace upon failure policy and inspection cost for CBM; and some components have rather complicated inter relationships. For example, in order to obtain lower life cycle cost, both lower operating cost and longer life are desirable, but operating cost is function of truck life. As truck gets older (or more mileage), the condition of truck worsens, causing operating cost to increase. Another example is that longer truck life can be achieved by performing more frequent truck inspection, but the price is the higher inspection cost. This will be discussed in detail in the later section. The relations among the component of equation 2.1 are illustrated in figure 4.1.

Figure 4.1 Maintenance Policy and Life Cycle Cost



The economic model is to determine the right condition limit which will result in the lowest life cycle cost of freight car truck for CBM. A factor that ties all the components with those inter-effecting relations together and ultimately determines the outcome for CBM is the condition limit. A freight car truck has to be replaced once the inspection approach determines or predicts that the internal condition of the freight car truck is over this condition limit. Therefore the condition limit determines the length of the truck life, and total operating cost. It also effects the inspection interval.

In order to develop the economic model, a number of parameters and mathematical relations are used. Some of them are just cited from the reports of other related researches and studies, such as Little's doctoral dissertation on freight car reliability [Little, 1991], AAR Facility for Accelerated Service Testing (FAST) / Heavy Axle Load (HAL) studies. Some of them, such as some relations, i.e., operating cost vs. freight car truck age, freight car truck deterioration rate vs. freight car truck age, and distribution curve for the length of freight car truck life, were first hypothesized based on the past studies, then modified and finalized into mathematical representations after author of this thesis had discussions with railroad engineers[1], officers, AAR researchers and experts in this field. These hypothesis relations are to demonstrate how they can be utilized in the CBM.

In this chapter, first, each component of equation 2.1 is described in the context of freight car truck maintenance (section 4.2). Second, three sub-models, which are operating cost model, truck life model and inspection interval model are presented (section 4.3, 4.4 and 4.5). Third, life cycle cost under imperfect inspection is discussed (section 4.6). Finally, the integrated model and result are presented (section 4.6).

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[1] In 1996, Author of this thesis had an opportunity to visit one of North American railroads' car shop and then conducted a one-week field study in this car shop. During this field study, author collected a set of freight car truck repairing data, and also had many long discussions with the officers and engineers on these issues.

4.2. Description of Components for Life Cycle Cost in The Context of Freight Car Truck

Initial Cost is the cost for buying a new freight car truck. In this economic model, the standard truck has an initial cost of $3,500.

Installation Cost is the cost associated with the truck replacement. It occurs when new truck has to be installed to a car. The replacement cost includes switching cost and installation cost. To avoid double counting, the cost of the truck, which is initial cost, is not included here. It is believed that this replacement cost is about $1,100 [Little, 1991], and is same for all three policies.

Salvage Cost is obtained because trucks are still in fair shape and can be rebuilt whey they are replaced. This is a negative number when it is added to the total cost. Under replace upon failure policy, the truck would be totally worn out when it is replaced, the value is very small. For other two policies, standard truck may get $500 [Little, 1991].

Failure Cost occurs when rail car truck fails during service. When some components of truck, such as spring assembly, snubber, or side bearing assembly are partially broken or missing, the rail car will fail, and be bad ordered. Then additional switching job has to be done, and the car body and track may have to be repaired if they are damaged. It is estimated that the average cost for this type is $750. Note that the failure of truck could also cause some serious event, such as derailment. However, this is very infrequent, it is not modeled here.

Operating cost, inspection cost and truck life are going to be calculated and discussed in detail in each corresponding sub-model.

The values for above cost components are summarized in table 4.1.

Table 4.1 Life Cycle Cost Components for Standard Truck

Cost Components	Value	Notes
Initial Cost	$3,500	Same for all maintenance policies.
Installation Cost	$1,100	Same for all maintenance policies.
Salvage Cost	-$500	Not applied to replace upon failure policy.
Failure Cost	$750	Applied to replace upon failure policy.
Operating Cost		To be calculated by using operating cost model.
Inspection Cost		To be calculated by using inspection interval model.

4.3. Operating Cost Model

Recall from chapter 3, overview of train-track system and three-piece truck, that freight car truck performs several functions. Each function leads to the incurrence of costs as the freight car is operated to provide service. The internal condition of the truck will become worse as the service time of the freight car is getting longer, and these costs will be increased.

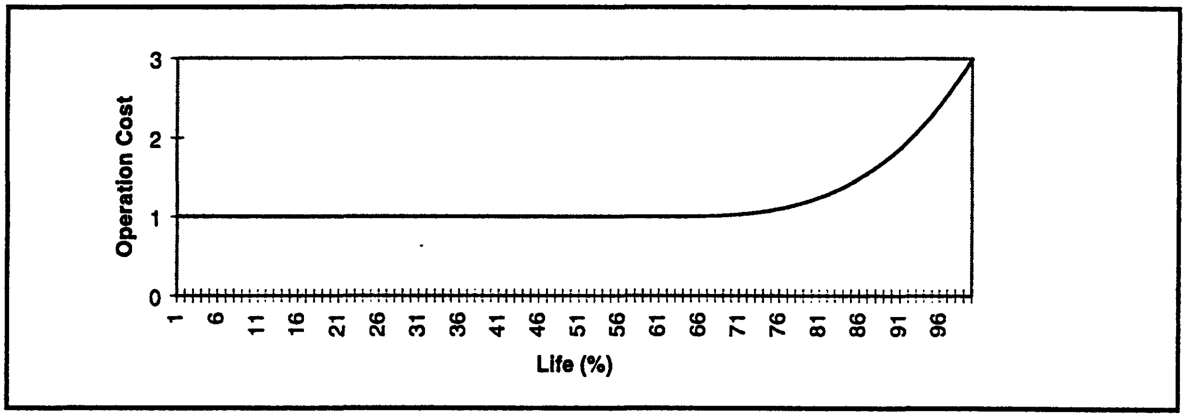
The first function the truck provides is guidance. Shortcomings in the guidance function lead to wear of the wheel flange and the gage face of the rail during curving, and during high speed operations that result in truck hunting, sustained lateral oscillatory instability, and to increased fuel consumption during periods of high creep forces between the wheel flange and the rail, whether due to curving, hunting, or steering bias which does not allow consistent flange-free operation in tangent track.

The second major function of the truck is to support the freight car vertically and to control the vertical dynamic loadings introduced between the freight car body and the track as the freight car moves over track irregularities. Inadequate damping of the vertical dynamic loads by the freight car truck results in fatigue and impact damage to the entire car body. Incorporating sufficient strength into the car body design to prevent fatigue leads to increased car tare weight, reducing energy efficiency and load carrying capacity. The truck also transmits vertical dynamic loads down into the track structure, particularly the rail, which shortens the life of rail through accelerating rail fatigue, and to lesser extent, the lives of ties and surfacing cycles.

The final major performance dimension of the freight car truck is longitudinal resistance to the forward motion of the train. This resistance results from bearing resistance, energy dissipation in the suspension system, energy dissipation in the wheel-rail interface, and the weight of the freight car including the weight of the truck. This resistance requires expenditures on fuel, locomotives, and locomotive maintenance that can be reduced if train resistance is minimized. The above are the components of operating cost due to freight car truck.

From the field experience, the operation cost curve over the life of truck can be thought as in figure 4.2. In this figure, X-axis is percentage of truck life and Y-axis is the cost factor. If we specify the additional operation cost when new truck is just installed as factor 1, then for a long period of truck life (from 0 to 60 percent of life), the cost keeps unchanged, but gradually, truck is worn out and truck's functionality goes down, the operation cost increases, it would goes as high as 3 times of normal cost. The average truck live (in terms of mileage) is 750,000 miles for standard truck, as used in HAL study. This number is used as the 100 percent life for standard trucks. The base operating cost is about $ 5.887 per 1000 miles. This is consistent with HAL Phase III study.

Figure 4.2. Freight Car Truck Operating Cost Curve



The curve can be mathematically represented as

$$Y = C*[(Max(x,A) - A)/100]^{B} + 1, \tag{4.1}$$

where Y is the operating cost at the point where a freight car truck has passed x percent of its life; $A = 60$ is the point where operating cost starts to increase; C and B are two constants to fit the curve, here $C = 40$ and $B = 3.2695$.

Based on this curve, for every given mileage of a truck life, this model first converts it to percentage of life, assuming that 100% life is the average life of a standard truck, or 750,000 miles. For example, if a freight car truck has 500,000 miles on it, then it has 500,000/750,000 = 66.6% life finished. Second, it computes the cumulative operation cost from its beginning to current stage. Finally the operating cost per unit (mile) is calculated. The result of this model is summarized in table 4.2. The first column is the percentage of life of a freight car truck. The second column is the corresponding miles, noting that the full life (100%) is 750,000 mile for standard truck. The third column is the cumulative operating cost for a truck and the last column is the average operating cost. From 0 to 60, even 70 percent, the operating cost doesn't change much. After this, it gradually increases as a truck comes to its end of service.

Note that it is assumed here that this is applied to large fleet with steady state truck life. The truck life is equally distributed among the fleet. Because of this, net present value is not used.

Table 4.2 Freight Car Truck Life and Operating Cost

(Standard Truck)

Freight Car Truck Life (%)	Freight Car Truck Life (Miles)	Cumulative Operating Cost ($)	Average Operating Cost ($/Mile)
0 - 60	0 - 450,000	0 - $ 2,649	$ 0.005887
65	487,500	$ 2,870	$ 0.005887
70	525,000	$ 3,093	$ 0.005892
75	562,500	$ 3,326	$ 0.005913
80	600,000	$ 3,580	$ 0.005966
85	637,500	$ 3,874	$ 0.006077
90	675,000	$ 4,233	$ 0.006272
95	712,500	$ 4,691	$ 0.006584
100	750,000	$ 5,287	$ 0.007050

4.4. Truck Life Model for Periodic Replacement Policy

This model is to determine the cut-off limit for periodic replacement policy. Periodic replacement policy, is a maintenance policy that a truck will be replaced when its service time (in term of mileage) reaches the predetermined cut-off limit. The principle to set up a cut-off limit is that according to this cut-off limit, the majority of freight car trucks are replaced before they become failure. Even for a small railroad, it may have several thousand cars, not to say those Class I railroads with 10 times more cars. The life of trucks varies a lot because of the different route, usage pattern and commodity type. This model takes the average truck life and its standard deviation of a railroad as input to determine the cut-off limit, which then becomes the average truck life for periodic replacement policy.

In last section, we have used 750,000 miles as the average life for a standard truck. A freight car truck can last from 500,000 miles to 1000,000 miles. Because of this range, a standard deviation of 80,000 miles is assumed. It is also assumed that freight car life has a normal distribution. The cumulative probability distribution value (CDV), or cumulative failure rate, and corresponding life (mileage) for truck are listed in table 4.3, and the plot is presented in figure 4.3. For example, in figure 4.3, CDV is 0.5 at average life of 750,000 miles, which means about 50% trucks may have a life equal to or longer than 750,000 miles and 50% trucks have ended their life before reaching 750,000 miles. PDV is probability density value, or the probability that trucks can last for a given length of life.

There is a tradeoff between the cost of potential failure and the cost that truck would not have its full length of life when it comes to select a cut-off limit for periodic replacement policy. If we want to have low or no failure rate, we can choose a very low cut-off limit, but this would cause trucks to have shorter life.

According to this curve, we select 544,000 miles as cut-off limit for periodic replacement policy. At this point, on average only 0.5% of trucks have failed, or 99.5% of trucks are before their failures. Recall when trucks fail, it may cause varied consequence, most time just bad orders. This ensures the benefit of periodic replacement policy, which is none or close to 0 failure cost.

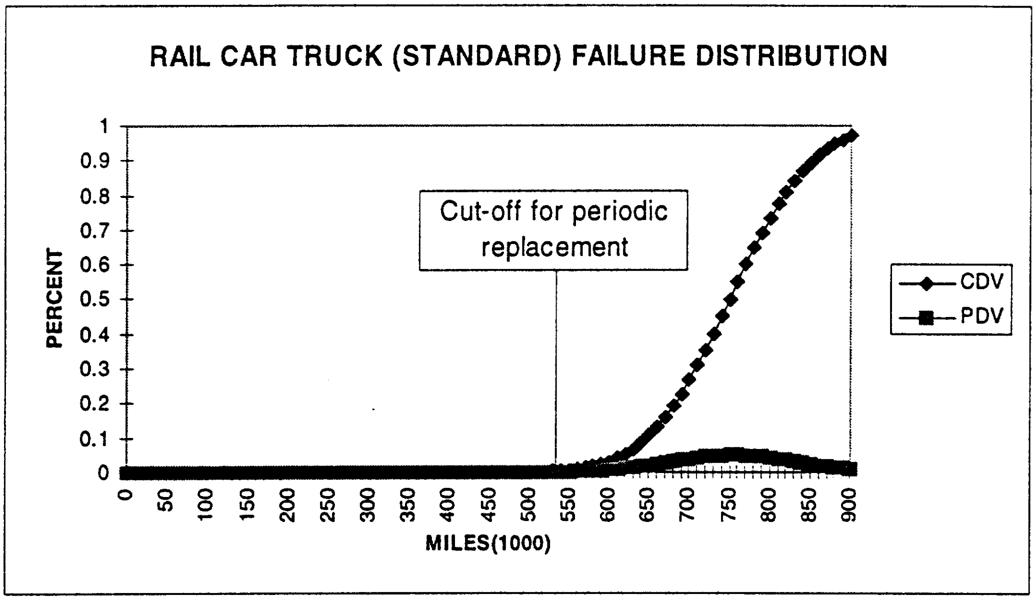
Table 4.3 Cumulative Failure Rate

and Life for Standard Truck

Cumulative Failure Rate	**Truck Life (miles)**
0.0001	452,442
0.005	543,933
0.1	647,476
0.2	682,670
0.3	708,048
0.4	729,732
0.5	750,000
0.6	770,268
0.7	791,952
0.8	817,330
0.9	852,524
0.99	936,107
Note: Average Truck Life = 750,000 miles **Standard Deviation = 80,000 miles**	

Figure 4.3 Cut-Off Limit for Periodic Replacement Policy and

Rail Car Truck Life Distribution

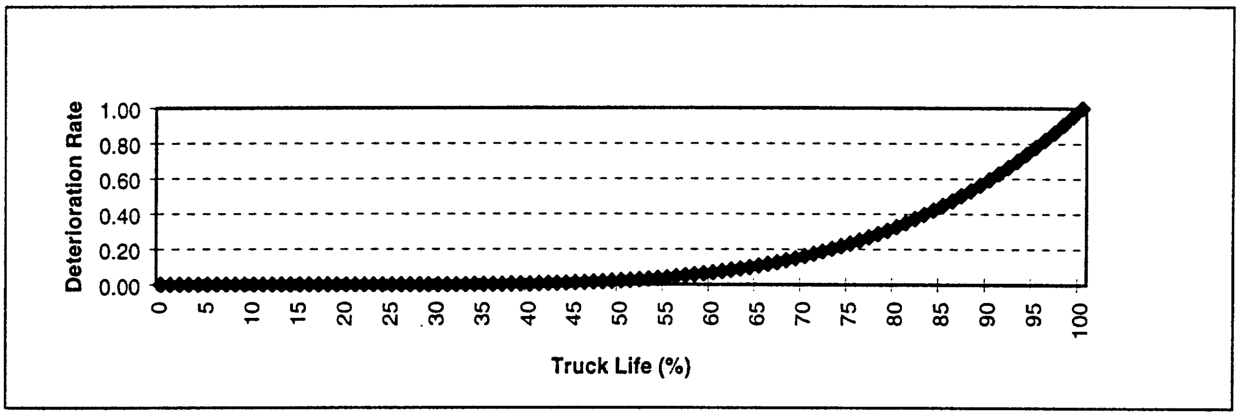


4.5. Inspection Interval Model

As discussed earlier, a very important process in CBM is inspection. This leads to additional inspection cost to truck maintenance cost comparing to periodic replacement and replace-on-failure policy. How often to inspect trucks is a very important problem and is one of key issue in implementing CBM. If inspection is done in very frequently, inspection cost could become very high, therefore reducing the benefits CBM has over the other two maintenance polices. On the other hand, if inspection interval is too long, then the truck could fail before the next inspection, which would result in failure cost.

Similar to the operation cost curve, there is a truck deterioration curve, as shown in figure 4.4, which describes the relation between the deterioration process and truck life.

Figure 4.4 Freight Car Truck Deterioration Curve



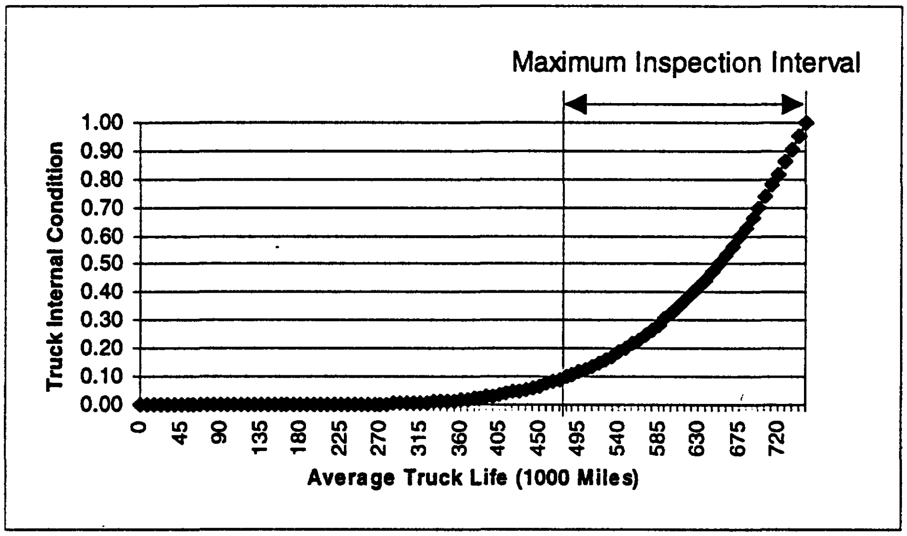
The inspection interval model is to determine the optimal condition limit and corresponding inspection interval. It is illustrated in figure 4.5. First, truck condition is divided into ten stages (Y-axis in figure 4.5), while truck condition gets worse when the value of Y-axis increases, and it would fail if the condition researches 1.00. On the deterioration curve, each condition stage (value of Y-axis) corresponds a mileage representing truck's life. For example, if condition stage is 0.1, the corresponding truck life is about 482,000 miles.

Suppose we have set 0.1 as condition limit. If a truck's condition is over 0.1 from the current inspection, then the truck will be replaced. However, if the truck's condition is under 0.1, then it will be kept in service and the minimum it can be in service is 750,000 - 482,000 = 268,000 miles (when truck's condition is less than but close to 0.1). To prevent trucks that are still in service from failure, they have to be inspected within 268,000 miles. This is the maximum inspection interval as indicated in figure 4.5. Because 750,000 is the average full life for a standard truck before it fails, some trucks may have longer life and some may have shorter life, therefore the inspection interval has to be shorter than 268,000 miles in order to catch the trucks with life less than 750,000 before they fail. Here we choose a factor of 0.6 of this maximum inspection interval, which is 161,000 miles as inspection interval - if condition limit is set to be 0.1. Similarly, inspection interval for other condition limits can be determined.

After inspection interval is determined, the average truck life, under the given condition limit, can be computed. Back to the case that condition limit is 0.1, the corresponding life is 482,000 miles, and the inspection interval is 161,000 miles. Suppose a truck's condition is around 0.1 when an inspection is performed. If the condition of the truck is over 0.1, then it will be replaced, the total life of this truck is about 482,000 miles; if the condition of truck is less than 0.1, then it will be left in service but will be caught in the next inspection, and be replaced. In this case, the truck will have 482,000 + 161,000 (inspection interval for condition limit 0.1) = 643,000 miles. Therefore it can be argued that the average life of a standard truck is about (482,000+643,000)/2, or 482,000+(161,000/2) = 562,000 miles.

After the average life and inspection interval are calculated for each condition limit, the inspection cost and additional operation cost are computed. Finally, life cycle cost of truck for each given condition limit is calculated.

Figure 4.5 Inspection Interval Determination



The result is listed in table 4.4. For example, if condition limit is 10%, then according to figure 4.4, when a truck is in this condition, its life is 64.2% × 750,000 = 482,000 miles. Then the inspection interval is set to (750k-482k)*0.6 = 161k miles. The average life is calculated as 482k + (161k/2) = 562k miles. The inspection cost is the product of cost/inspection and number of inspections. From field visits and discussion with field engineers, we estimate an inspection may take average 36 minutes for an inspector with $40/hour pay rate. The cost per inspection rate then is $24/inspection. Number of inspections is computed as 562k (average life) / 161k (inspection interval). With average life of 562k miles, the average operating cost is computed in operating cost model as discussed before. Finally the life cycle cost when condition limit is 10% is calculated according to equation 2.1.

Table 4.4 CBM: Optimal Condition Limit and Inspection Interval

Under Perfect Inspection

True Condition	Life at Condition (1k miles)	Inspection Interval (1k miles)	Average Life (1k miles)	Inspection Cost	Operating Cost	Life Cycle Cost ($/mile)
0.10	482	161	562	$80	$ 3,324	$ 0.01299
0.20	547	122	608	$114	$ 3,635	$ 0.01259
0.30	590	96	638	$152	$ 3,878	$ 0.01243
0.40	624	76	662	$200	$ 4,091	$ 0.01238
0.50	652	59	681	$265	$ 4,309	$ 0.01244
0.60	676	44	698	$360	$ 4,499	$ 0.01254
0.70	697	32	713	$517	$ 4,696	$ 0.01278
0.80	717	20	727	$827	$ 4,904	$ 0.01326
0.90	734	10	739	$1,755	$ 5,129	$ 0.01460
0.99	748	1	749	$16,300	$ 5,279	$ 0.03403

Table 4.4 shows that when condition limit is set to be 0.40, CBM would result in the lowest life cycle cost ($ 0.01238 / mile) among all possible condition limits.

4.6. Life Cycle Cost Under Imperfect Inspection

Note that the result of table 4.4 is obtained when it is assumed that inspection is perfect, or truck's internal condition can be assessed with 100 accuracy from external inspection. However, the inspection result was not perfect, as discussed in chapter 3, the best could be obtained was 75 percent, while false alarm rate as high as 67 percent (Table 3.2). False alarm means that the inspection model tends to overestimate the wear of truck. This section is to show how the accuracy of an inspection approach can effect the life cycle cost under CBM policy.

In order to analyze the freight car life cycle cost under imperfect inspection when CBM is implemented, we construct table 4.5 which shows the relation between real truck condition and perceived condition from a inspection. This is done by incorporating the results from table 3.2. Table 3.2 shows that the inspection approach presented by this research has about 75% correct prediction rate, and out of 25% incorrectly predicted, 3/60 = 5% are underestimated (false positive), 12/60 = 20% are overestimated (false alarm). Therefore, for a truck with real condition of *C*, there are 75% chance that the estimated condition after inspection is *C*, 5% chance that the estimated condition is less than *C* and 20% chance that the estimated condition is greater than *C*. We assume that if it is less than *C*, then 3% falls to $C - 0.1$ and 2% falls to $C - 0.2$, and if it is greater than *C*, then 13% falls to $C + 0.1$, and 7% falls to $C + 0.2$. In table 4.5, it shows that if the real condition of a truck is 0.4 (column 6), there are 2% chance that the estimated condition after inspection is 0.2, 3% chance that the estimated condition is 0.3, 75% chance that the estimated condition is 0.4% (correct), 13% chance that the estimated condition is 0.5 and 7% chance that the estimated condition is 0.6.

Note that the distribution is same for every real condition in table 4.5. It can be argued otherwise. Sine the real distribution can be obtained only after CBM is implemented, here we just use this as a way to demonstrated how the life cycle cost under imperfect inspection can be analyzed.

Table 4.5 Real Condition Vs. Perceived Condition

Perceived Condition (Worn)	Real Truck Condition (Worn)										
	<0.1	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	>0.9
<0.1	75%	3%	2%								
0.1	13%	75%	3%	2%							
0.2	7%	13%	75%	3%	2%						
0.3		7%	13%	75%	3%	2%					
0.4			7%	13%	75%	3%	2%				
0.5				7%	13%	75%	3%	2%			
0.6					7%	13%	75%	3%	2%		
0.7						7%	13%	75%	3%	2%	
0.8							7%	13%	75%	3%	2%
0.9								7%	13%	75%	3%
>.9									7%	13%	75%
Distribution			100%	93.0%	74.4%	3.7%					
Weight(<=0.4)			93.0%	74.4%	3.7%	0.074%					
Weight(>=0.4)			7%	18.6%	70.7%	3.646%					

Now take a look at what happens to a freight car truck if CBM is applied under imperfect inspection. Assume the condition limit is 0.4. A new freight car truck is put in service. It will be inspected according to the interval computed in table 4.4. It will not be until its real condition reaches 0.2 that there are some probability that it will be replaced after the inspection (column 4 of table 4.5). If a truck's condition is less than or equal to 0.1, then the highest perceived condition is 0.3, still less than condition limit 0.4, therefore it will not be replaced with any probability. When its real condition reaches 0.2, there is 7% chance that the truck is estimated to have condition 0.4, in other words, about 7% of trucks on average will be replaced when their real conditions are 0.2 with the condition limit 0.4 under this inspection approach. The remaining 93% trucks will reach real condition 0.3, while of this 93% remaining trucks, 13% will be perceived to reach 0.4 and 7% reach 0.5, therefore they will be replaced. Coming to this point, the real condition is still less than 0.4, thus those replacements should not have occurred if it was under perfect inspection. It results in a shorter life for those trucks being replaced.

Continuing to be in the service, the real condition of trucks will reach 0.4, but 2% of those trucks will be perceived 0.2 and 3% perceived 03, thus 5% of them will not be replaced. Rest 95% will be perceived equal or over 0.4, and will be replaced. The 5% of trucks with real condition 0.4 will be kept in service and eventually reach real condition 0.5. When inspection is performed, only 2% of the trucks with real condition 0.5 are perceived less than 0.4 (0.3); they will be kept in service and will probably fail eventually. The rest of 98% of trucks with real condition 0.5 will be replaced since their perceived conditions are over 0.4.

The replacement process as truck deteriorates is shown in figure 4.6. The condition limit is 0.4. The number in small font is the overall percentage or weight given that it all starts from real condition 0.2. For example, when real condition is 0.4, 95% of the trucks will be replaced, but the overall percentage is 95%*80%*93% = 70.68%.

Finally, life cycle cost under imperfect inspection is calculated. Because the inspection is imperfect, some trucks will be replaced early, some will be replaced late, some are going to fail, and majority will be on time. Therefore the life cycle cost for a condition limit is a weighted number. The results are listed in table 4.6.

Figure 4.6 Percentage of Replacement Under Different Condition Stage

for Condition Limit 0.4

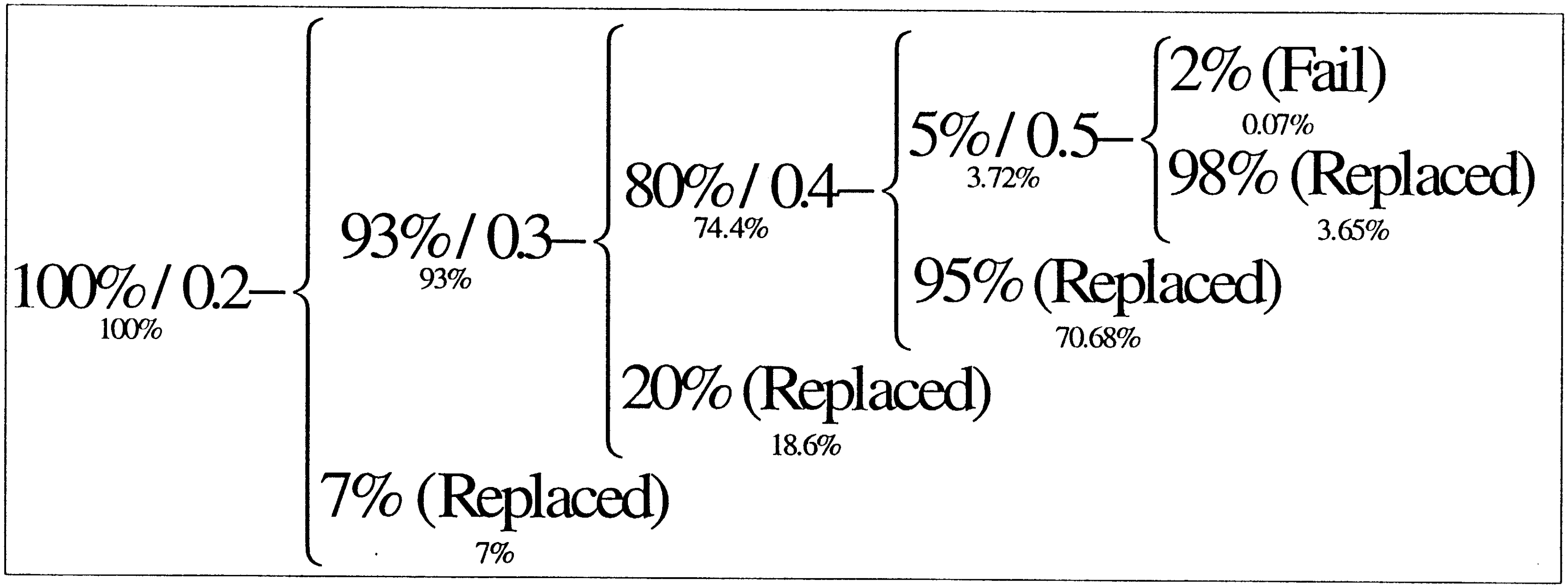


Table 4.6 CBM: Life Cycle Cost Under Imperfect Inspection

(Standard Truck)

Condition Limit	Real Condition (Worn)	Perceived Condition (Worn)	Weight	Con-sequence (Replaced -)	Average Life (1k mile)	Inspect Cost ($)	Operating Cost ($)	Failure Cost ($)	Salvage Cost ($)	Initial Cost ($)	nstallatio Cost ($)	Total Cost ($)	Life Cycle Cost ($/mile)
0.3	0.1	>=0.3	0.0700	Very early	562	$ 80	$ 3,324	$ -	$(700)	$3,500	$1,100	$ 7,304	0.01300
	0.2	>=0.3	0.1860	Early	608	$ 114	$ 3,635	$ -	$(700)	$3,500	$1,100	$ 7,649	0.01258
	0.3	>=0.3	0.7068	On time	638	$ 152	$ 3,878	$ -	$(700)	$3,500	$1,100	$ 7,930	0.01243
	0.4	>=0.3	0.0365	Late	662	$ 200	$ 4,091	$ -	$(700)	$3,500	$1,100	$ 8,191	0.01237
	0.4	<0.3	0.0007	Fail	750	$ 152	$ 5,279	$750	$ -	$3,500	$1,100	$ 10,781	0.01437
	Weighted		1.0000		628	$ 142	$ 3,803	$ 1	$(699)	$3,500	$1,100	$ 7,845	0.01250
*0.4 (The best)	0.2	>=0.4	0.0700	Very early	608	$ 114	$ 3,635	$ -	$(700)	$3,500	$1,100	$ 7,649	0.01258
	0.3	>=0.4	0.1860	Early	638	$ 152	$ 3,878	$ -	$(700)	$3,500	$1,100	$ 7,930	0.01243
	0.4	>=0.4	0.7068	On time	662	$ 200	$ 4,091	$ -	$(700)	$3,500	$1,100	$ 8,191	0.01237
	0.5	>=0.4	0.0365	Late	681	$ 265	$ 4,309	$ -	$(700)	$3,500	$1,100	$ 8,474	0.01244
	0.5	<0.4	0.0007	Fail	750	$ 265	$ 5,279	$750	$ -	$3,500	$1,100	$ 10,894	0.01452
	Weighted		1.0000		655	$ 187	$ 4,028	$ 1	$(699)	$3,500	$1,100	$ 8,117	0.01240
0.5	0.3	>=0.5	0.0700	Very early	638	$ 152	$ 3,878	$ -	$(700)	$3,500	$1,100	$ 7,930	0.01243
	0.4	>=0.5	0.1860	Early	662	$ 200	$ 4,091	$ -	$(700)	$3,500	$1,100	$ 8,191	0.01237
	0.5	>=0.5	0.7068	On time	681	$ 265	$ 4,309	$ -	$(700)	$3,500	$1,100	$ 8,474	0.01244
	0.6	>=0.5	0.0365	Late	698	$ 360	$ 4,499	$ -	$(700)	$3,500	$1,100	$ 8,759	0.01255
	0.6	<0.5	0.0007	Fail	750	$ 265	$ 5,279	$750	$ -	$3,500	$1,100	$ 10,894	0.01452
	Weighted		1.0000		675	$ 248	$ 4,246	$ 1	$(699)	$3,500	$1,100	$ 8,395	0.01243
0.6	0.4	>=0.6	0.0700	Very early	662	$ 200	$ 4,091	$ -	$(700)	$3,500	$1,100	$ 8,191	0.01237
	0.5	>=0.6	0.1860	Early	681	$ 265	$ 4,309	$ -	$(700)	$3,500	$1,100	$ 8,474	0.01244
	0.6	>=0.6	0.7068	On time	698	$ 360	$ 4,499	$ -	$(700)	$3,500	$1,100	$ 8,759	0.01255
	0.7	>=0.6	0.0365	Late	713	$ 517	$ 4,696	$ -	$(700)	$3,500	$1,100	$ 9,113	0.01278
	0.7	<0.6	0.0007	Fail	750	$ 360	$ 5,279	$750	$ -	$3,500	$1,100	$ 10,989	0.01465
	Weighted		1.0000		693	$ 337	$ 4,443	$ 1	$(699)	$3,500	$1,100	$ 8,681	0.01253

In table 4.6, life cycle cost is calculated for condition limit 0.3, 0.4,0.5 and 0.6 to find the lowest. Condition limit 0.4 is still the best as it is under perfect inspection. The life cycle cost is only slightly higher than it is under perfect inspection. This is because some trucks are replaced earlier and some are replaced later than they should be.

One thing that is worth noting in table 4.5, figure 4.6 and table 4.6 is that, even if the inspection approach presented has a correct prediction rate of 70 - 80%, the overall failure rate is very low, only 0.07%. Recall that of the trucks that fail, the great majority of them just cause bad orders. Therefore, safety is not an issue.

4.7. Sensitivity Analysis

In this section, sensitivity analysis is performed. The study area is distribution of real condition over perceived condition (table 4.5). We wish to see how the inspection accuracy affects the truck life cycle cost (LLC) under CBM.

In last section, we have assumed that if the real condition is *C*, then the perceived condition can be $C - 0.1$, $C - 0.2$, C, $C + 0.1$ and $C + 0.2$ with the distribution of 2%, 3%, 75%, 13% and 7%, respectively. In this sensitivity analysis, we are going to assume other distributions. The alternative distribution assumptions alone with the one we used in last section are listed in table 4.7.

Table 4.7. Real Condition Distribution Assumptions

Perceived Condition	**Distribution for Real Condition *C***			
	Base Case	**Case 1**	**Case 2**	**Case 3**
C - 0.2	0%	2%	4%	10%
C - 0.1	0%	3%	6%	15%
C	100%	75%	50%	50%
C + 0.1	0%	13%	26%	15%
C + 0.2	0%	7%	14%	10%

Note that in table 4.7, the base case is perfect inspection; if the real condition of a truck is *C*, then it will be perceived as *C* with 100% probability after the inspection. Case 1 is based upon actual inspection performance. In Case 2, the false alarm rate is doubled relative to Case 1. In case 3, the overall correct prediction rate is the same as Case 2, but is distributed with a balance over the real condition.

The life cycle cost under different condition distribution is listed in table 4.8. It shows that under Case 2, which has much higher false alarm rate, the life cycle cost increases more for condition limit 0.3 and 0.4, but decreases more for condition limit 0.5, 0.6, comparing to Case 1. This is because, with the higher false alarm rate, more trucks are replaced earlier than they should be. Given that condition 0.4 is the best choice which can result in the lowest life cycle cost under perfect inspection, for condition limit 0.3 and 0.4, higher false alarm rate causes trucks to be replaced far earlier than the optimal condition limit 0.4, therefore, the life cycle cost increases. On the other hand, for condition limit 0.5 and 0.6, higher false alarm rate make trucks replaced more close to optimal condition limit 0.4, therefore, the life cycle cost decreases.

Table 4.8 Sensitivity Analysis for Imperfect Inspection

Condition	Base Case	Case 1		Case 2		Case 3	
Limit	LCC	LCC	Change	LCC	Change	LCC	Change
0.3	$ 0.01243	$ 0.01250	0.56%	$ 0.01256	1.09%	$ 0.01254	0.95%
0.4	$ 0.01238	$ 0.01240	0.20%	$ 0.01243	0.42%	$ 0.01245	0.62%
0.5	$ 0.01244	$ 0.01243	-0.01%	$ 0.01243	-0.08%	$ 0.01248	0.33%
0.6	$ 0.01254	$ 0.01253	-0.14%	$ 0.01250	-0.32%	$ 0.01258	0.27%

Overall, with the variation of distribution of real condition over perceived condition, life cycle cost doesn't change significantly. It increases or decreases less than 1%. This shows that the results from CBM are very robust.

4.8. Integrated Model and Results

By incorporating the above models into an integrated study, we obtain the following results listed in table 4.9. This table shows the life cycle cost of a truck under three maintenance policies, i.e., periodic replacement, replace upon failure, condition-based maintenance and CBM with imperfect inspection.

Maintenance Policy	Initial Cost	Inspection Cost	Replace-ment Cost	Failure Cost	Operating Cost	Salvage Cost	Total Cost	Truck Life (miles)	Life Cycle Cost ($/mile)
Periodic Replace-ment	$ 3,500	$ 0	$ 1,100	$ 0	$ 3,210	$ (700)	$ 7,110	543,933	0.013072
Replace upon Failure	$ 3,500	$ 0	$ 1,100	$ 750	$ 5,287	$ (0)	$ 10,637	750,000	0.014183
Condition-Based Maintenance(Perfect Inspection)	$ 3,500	$ 200	$ 1,100	$ 0	$ 4,091	$ (700)	$ 8,191	662,000	0.012377
Condition-Based Maintenance (Imperfect Inspection)	$ 3,500	$ 187	$ 1,100	$ 1	$ 4,028	$ (699)	$ 8,117	654,514	0.012402

Table 4.9 Life Cycle Cost of Freight Car Truck Based on Three Maintenance Policies

Here is how the results are obtained. As expressed by equation 2.1, life cycle cost for a truck is the sum of initial cost, inspection cost, failure cost, operating cost and salvage cost divided by the life of the truck. In table 4.9, the first column is initial cost, which is $3,500, same for every policy. The second column is inspection cost, which only occurs under CBM; $0 for periodic replacement and replace upon failure policy, S200 for CBM under perfect inspection and $187 under imperfect inspection. It is calculated by using the Inspection Interval Model discussed in last section. The third column is replacement cost, which is $1,100 for every policy.

The fourth column is failure cost. There is a small amount failure cost for periodic replacement that is only applied to the replace upon failure policy, S750.

Operating cost is in the sixth column, which is calculated by using Operating Cost model. The next column is salvage cost, replace upon failure does not have such cost, but $700 for other two policies. Adding above costs together along each row, we have the total cost in eighth column. The ninth column is life of a truck under difference policy. For periodic replacement policy, it is calculated in Truck Life model. Since the average life of a standard truck is 750,000 miles, we use this number for replacement upon failure model. The life of a truck under CBM is obtained in the Inspection Interval model. Finally, the life cycle cost of a standard truck under each maintenance policy is calculated with total cost divided by the life of truck, which is presented in the last column.

Among three policies, CBM results in the lowest life cycle cost, even with imperfect inspection. It is followed by periodic replacement policy and replace upon failure policy. The reason for this result is, as table 4.9 shows that, comparing to other two policies, CBM has very low failure cost, low operating cost, some salvage cost, some small amount of inspection cost and longer life. This result fits the general discussion of maintenance policy in chapter 2 very well.

Another advantage CBM has over the other maintenance policies is that, even with imperfect inspection, CBM results in the lowest failure rate. The impact of this is not easily being observed from the result of life cycle because, the failure cost used in estimating life cycle cost only included the cost of additional switching job, repairing work due to bad order caused by failed truck. It did not include the cost of some serious problem caused by truck failure, such as derailment, as it is very rare that truck failure causes such problem. Therefore, if CBM is implemented, railroads can improve their safety record.

Chapter 5

A Policy Analysis: Premium Truck vs. Standard Truck

5.1. Introduction

Improved trucks, or premium trucks (even though they are exchangeable, we will use premium truck most time in this discussion), have been proven to have better performance than standard trucks [Read and Kalay, 1996]. However, they are also more expensive than strand trucks. Freight car owners face the question that whether they should use premium truck or standard truck.

The economic model presented in the last chapter can be used to address this issue and give some insights from the life cycle cost point of view. In this chapter, first, some necessary cost components for premium trucks are discussed and presented (section 5.2). Second, CBM is applied to premium truck maintenance, and life cycle cost is calculated (section 5.3). Finally, premium trucks are compared to standard trucks under the three alternative policies (section 5.4).

5.2. Cost Components for Premium Truck

In this section, first, some necessary cost parameters and relations are discussed for the economic model to be applied to premium truck, just as we did in chapter 4 for standard trucks. Then the results from the economic model are presented.

Initial Cost for premium truck is $5,300, higher than standard truck.

Installation Cost is the same for premium truck as standard truck, $1,100.

Salvage Cost is higher for premium truck than for standard truck because the initial cost for premium truck is higher. It is $1,060 for premium truck.

Failure Cost is again referred to the cost when components of truck are broken and cause bad order. It is same for both premium truck and standard truck to be switched to the repairing shop. It is $750.

The above cost parameters are summarized in table 5.1.

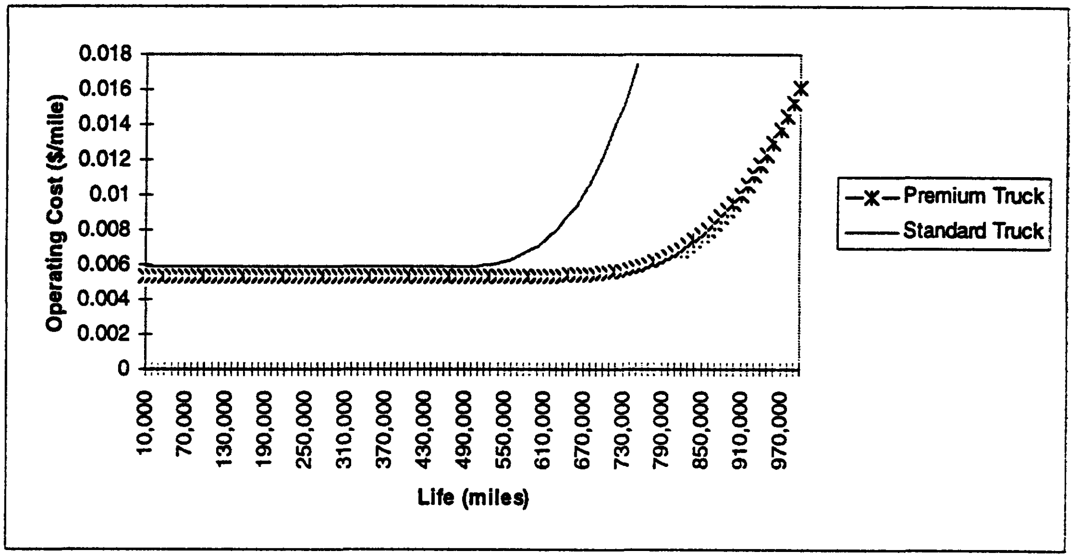
Table 5.1 Comparison on Cost Components between Standard and Premium Truck

Cost Components	**Standard Truck**	**Premium Truck**	**Notes**
Initial Cost	$3,500	$5,300	Same for all maintenance policies.
Installation Cost	$1,100	$1,100	Same for all maintenance policies.
Salvage Cost	($500)	($1,060)	Not applied to replace upon failure policy.
Failure Cost	$750	$750	Additional switching job for bad order.
Operating Cost			To be calculated by using operating cost model.
Inspection Cost			To be calculated by using inspection interval model.

Initial results of Phase III testing at the Transportation Technology Center, Facility for Accelerated Service Testing (FAST), suggest that premium truck with improved suspension system will substantially improve the economics of operating 315,000-pound freight cars [Read and Kalay, 1996]. Benefits include reduced fuel consumption, less wheel/rail wear and other reductions in track damage. Therefore, premium truck will have lower operating cost.

Premium truck also has longer life than the standard truck. As presented in last chapter, average life for a standard truck is about 750,000 miles. For premium truck, the average life is about 1,000,000 miles. When standard truck starts to deteriorate rapidly after being in service for 600,000 miles and operating cost increases sharply, premium truck is still in good shape with constant low operating cost. It is only after being in service for 800,000 miles, the operating cost for premium truck starts to increase. Those comparison of operating cost between standard truck and premium truck can be seen in figure 5.1.

Figure 5.1 Operating Cost for Standard Truck and Premium Truck



5.3. CBM applied to Premium Truck

After those necessary parameters have been presented, CBM is applied to premium truck, followed the same procedure from chapter 5 when CBM is applied to standard truck. The result under perfection inspection is listed in table 5.2.

Table 5.2 CBM: Optimal Condition Limit and Inspection Interval for Premium Truck Under Perfect Inspection

True Condition	Life at Condition (1k miles)	Inspection Interval (1k miles)	Average Life (1k miles)	Inspection Cost	Operating Cost	Life Cycle Cost ($/mile)
0.10	642	215	750	$68	$ 4,043	$ 0.01261
0.20	729	163	810	$102	$ 4,413	$ 0.01217
0.30	787	128	851	$141	$ 4,699	$ 0.01196
0.40	832	101	882	$189	$ 4,949	$ 0.01187
0.50	869	78	909	$254	$ 5,202	$ 0.01188
0.60	901	59	931	$349	$ 5,424	$ 0.01194
0.70	930	42	951	$505	$ 5,652	$ 0.01209
0.80	955	27	969	$816	$ 5,894	$ 0.01244
0.90	979	13	985	$1,743	$ 6,154	$ 0.01344
0.99	998	1	998	$16,287	$ 6,328	$ 0.02800

Table 5.2 shows that life cycle cost of a premium truck is the lowest (0.01187$/mile) when condition limit is 0.4 and inspection interval is 101,000 miles, although it is only slightly higher (0.01188$/mile) when condition limit is 0.5.

Life cycle cost under imperfect inspection when CBM is applied is also analyzed for premium truck in the same way that is done to standard truck. The results are summarized in table 5.3.

From table 5.3 we can see that condition 0.5 would result in the lowest life cycle cost of $0.01189/mile, although condition 0.4 would have a slightly higher result. This is just the reverse order when inspection is perfect. The reason for this is that the inspection turns to overestimate the deterioration of a truck, when the perceived condition is 0.5, the real condition of some trucks more close to 0.4, which is the optimal condition limit under perfect condition.

Table 5.3 CBM: Life Cycle Cost Under Imperfect Inspection (Premium Truck)

Condition Limit	Real Condition (Worn)	Perceived Condition (Worn)	Weight	Con-sequence (Replaced -)	Average Life (1k mile)	Inspect Cost ($)	Operating Cost ($)	Failure Cost ($)	Salvage Cost ($)	Initial Cost ($)	nstallatio Cost ($)	Total Cost ($)	Life Cycle Cost ($/mile)
0.3	0.1	>=0.3	0.0700	Very early	749.69	$ 68	$ 4,043	$ -	$(1,060)	$5,300	$1,100	$ 9,451	0.01261
	0.2	>=0.3	0.1860	Early	810.14	$ 102	$ 4,413	$ -	$(1,060)	$5,300	$1,100	$ 9,855	0.01217
	0.3	>=0.3	0.7068	On time	850.84	$ 141	$ 4,699	$ -	$(1,060)	$5,300	$1,100	$ 10,180	0.01196
	0.4	>=0.3	0.0365	Late	882.4	$ 189	$ 4,949	$ -	$(1,060)	$5,300	$1,100	$ 10,478	0.01187
	0.4	<0.3	0.0007	Fail	1000	$ 189	$ 6,328	$750	$ -	$5,300	$1,100	$ 13,667	0.01367
	Weighted		1.0000		837	$ 130	$ 4,610	$ 1	$(1,059)	$5,300	$1,100	$ 10,082	0.01204
0.4	0.2	>=0.4	0.0700	Very early	810.14	$ 102	$ 4,413	$ -	$(1,060)	$5,300	$1,100	$ 9,855	0.01217
	0.3	>=0.4	0.1860	Early	850.84	$ 141	$ 4,699	$ -	$(1,060)	$5,300	$1,100	$ 10,180	0.01196
	0.4	>=0.4	0.7068	On time	882.4	$ 189	$ 4,949	$ -	$(1,060)	$5,300	$1,100	$ 10,478	0.01187
	0.5	>=0.4	0.0365	Late	908.54	$ 254	$ 5,202	$ -	$(1,060)	$5,300	$1,100	$ 10,796	0.01188
	0.5	<0.4	0.0007	Fail	1000	$ 254	$ 6,328	$750	$ -	$5,300	$1,100	$ 13,732	0.01373
	Weighted		1.0000		873	$ 176	$ 4,875	$ 1	$(1,059)	$5,300	$1,100	$ 10,393	0.01191
*0.5 (The best)	0.3	>=0.5	0.0700	Very early	850.84	$ 141	$ 4,699	$ -	$(1,060)	$5,300	$1,100	$ 10,180	0.01196
	0.4	>=0.5	0.1860	Early	882.4	$ 189	$ 4,949	$ -	$(1,060)	$5,300	$1,100	$ 10,478	0.01187
	0.5	>=0.5	0.7068	On time	908.54	$ 254	$ 5,202	$ -	$(1,060)	$5,300	$1,100	$ 10,796	0.01188
	0.6	>=0.5	0.0365	Late	931.04	$ 349	$ 5,424	$ -	$(1,060)	$5,300	$1,100	$ 11,113	0.01194
	0.6	<0.5	0.0007	Fail	1000	$ 349	$ 6,328	$750	$ -	$5,300	$1,100	$ 13,827	0.01383
	Weighted		1.0000		901	$ 237	$ 5,129	$ 1	$(1,059)	$5,300	$1,100	$ 10,707	0.01189
0.6	0.4	>=0.6	0.0700	Very early	882.4	$ 189	$ 4,949	$ -	$(1,060)	$5,300	$1,100	$ 10,478	0.01187
	0.5	>=0.6	0.1860	Early	908.54	$ 254	$ 5,202	$ -	$(1,060)	$5,300	$1,100	$ 10,796	0.01188
	0.6	>=0.6	0.7068	On time	931.04	$ 349	$ 5,424	$ -	$(1,060)	$5,300	$1,100	$ 11,113	0.01194
	0.7	>=0.6	0.0365	Late	950.9	$ 505	$ 5,652	$ -	$(1,060)	$5,300	$1,100	$ 11,498	0.01209
	0.7	<0.6	0.0007	Fail	1000	$ 505	$ 6,328	$750	$ -	$5,300	$1,100	$ 13,983	0.01398
	Weighted		1.0000		924	$ 326	$ 5,358	$ 1	$(1,059)	$5,300	$1,100	$ 11,025	0.01193

5.4. Premium Truck and Standard Truck under Alternative Maintenance Policies

The economic model also calculates the life cycle cost for premium truck under other two alternative policies, i.e., periodic replacement and replace upon failure. The overall results are presented in table 5.4.

There are four cases are listed in table 5.4. Life cycle cost under periodic replacement policy, replace upon failure policy, CBM with perfect inspection and CBM with imperfect inspection. Three out of these four cases, i.e., under replace upon failure policy, CBM with perfect inspection and imperfect inspection, premium truck would result in about 5% lower in life cycle cost than standard truck. In one case, which is under periodic replacement policy, premium truck would result in slightly higher life cycle cost than standard truck, but only by 0.2%.

Table 5.4 Life Cycle Cost : Premium Truck vs. Standard Truck

Mainteinance Policy	Truck Type	Initial Cost	Inspection Cost	Replace-ment Cost	Failure Cost	Operating Cost	Salvage Cost	Total Cost	Truck Life (miles)	Life Cycle Cost ($/mile)
Periodic Replacement	Stand	$3,500	$0	$1,100	$4	$3,210	($700)	$7,114	543,933	0.01308
	Premium	$5,300	$0	$1,100	$4	$3,716	($1,060)	$9,059	690,900	0.01311
Replace Upon Failure	Stand	$3,500	$0	$1,100	$750	$5,287	$0	$10,637	750,000	0.01418
	Premium	$5,300	$0	$1,100	$750	$6,436	$0	$13,586	1,000,000	0.01359
CBM (Under Perfect Insepction)	Stand	$3,500	$200	$1,100	$0	$4,091	($700)	$8,191	661,797	0.01238
	Premium	$5,300	$189	$1,100	$0	$4,949	($1,060)	$10,478	882,396	0.01187
CBM (Under Inperfect Inspection)	Stand	$3,500	$187	$1,100	$1	$4,028	($699)	$8,117	654,514	0.01240
	Premium	$5,300	$237	$1,100	$1	$5,129	($1,059)	$10,708	900,523	0.01189

One thing needs to be pointed out is that through this analysis, the assumption is that a car will run at least 100,000 miles annually is made. If the annual mileage is not high, the high initial cost would have weight in net present value of total cost, and standard trucks might be more economical than premium trucks.

Another factor that freight car owner should consider is how much could be the cost of commodity damage. When the truck gets order, the condition of truck deteriorates and it no longer runs smoothly; the movement of car could cause various kinds of damage to the commodities the car carries. It is the same reason that trucks with poor condition would cause higher operating cost. Depending on the value of commodity, this cost could be very high, if the commodity is auto part, or electric device; or it may not be significant, if the commodity is grain or coal. While premium trucks have been proven to have better performance, longer life, they also deteriorate later than standard trucks, thus they will reduce the cost from commodity damage if the commodity has high value.

Therefore, the conclusion is that premium would result in lower life cycle cost for the most maintenance policies if the annual mileage is high. When thinking of ordering new cars to carry high value commodity, with high annual mileage, premium trucks are recommended.

Chapter 6

Summary, Conclusion and Future Research

6.1. Summary of the thesis

This thesis seeks to apply condition based maintenance to rail freight car components, especially to rail car trucks, to achieve the lowest life cycle cost.

First alternative maintenance policies are reviewed, i.e., periodic replacement and replace upon failure. Varied policies for rail freight car maintenance not only have impact on car availability but also effect operating cost, freight damage rate and safety. The most commonly used policies in practice are to replace upon failure or to replace periodically. Problems associated with replacement upon failure are that it would result in a higher operating cost, incur failure cost and also raise safety concerns. For the periodic replacement policy, it is hard to decide the right life limit at which components will be replaced. The same components on different cars may have different lengths of physical lives because of different usage patterns. If the replacement limit is conservative, a risk exists that the component may be replaced under the scheduled maintenance regime well before its useful life has elapsed; this would result in excessive and unnecessary maintenance and higher life cycle costs. In the cases where the replacement limit is too optimistic, many components will fail before being replaced, and costs will be similar to replace upon failure.

Then, key issues of implementing a CBM are presented in chapter 2, section 2.3. It also shows how these issues can be addressed by reviewing the literature on medical examination and some CBM applications. The critical issues for a CBM program be success are the accuracy of inspection, selection of inspection interval and condition limit. In the field of medical examination, researchers attempt to recognize the trade off between costs of examination and losses due to late detection. Then statistical models are built to link the basic elements that are involved in screening, for example, the nature and history of the disease, type of screening tests, screening times, and treatments that follow a positive result. A solution usually can by derived based on the various assumptions of deterioration and failure distributions.

Because freight car trucks are located under the car body, it is not possible to examine the truck's internal condition without lifting car body off the trucks. Part of this research is to continue attacking this problem. The first part of chapter 3 reviews three-piece freight car truck structure and inspection practices. The second part of chapter 3 presents the results from continuous modeling effort to predict truck's internal condition by inspecting external parts.

An economic model is presented in chapter 4. This economic model illustrates how the maintenance policies effect the life cycle cost of freight car truck and how CBM can be implemented for freight car truck maintenance with the incorporation of the inspection approach.

In Chapter 5, the economic model is applied to premium truck under different maintenance policies to address the issue of premium truck vs. standard truck. Based on the result of the economic model, some conclusion is made.

6.2. Conclusion

This research builds a frame work on how to implement a successful CBM program for the maintenance of freight car components. It combines all of the critical issues, such as inspection accuracy, inspection interval and condition limit, into an economic model. It does so by recognizing the complicated inter-relationships between operating cost and life, inspection cost and life, and failure cost and inspection cost.

Condition based maintenance, if implemented properly, could result in lower life cycle cost than alternative maintenance policies, i.e., periodical replacement and replace upon failure. The reason for this is that compared to the other two policies, CBM has very low failure cost, low operating cost, some salvage cost, some small amount of inspection cost and longer life. This is supported by the results of the economic model. It shows CBM can save 5% to 12% of life cycle cost relative to two alternative maintenance policies, that even when the inspections are not perfect (i.e., a 70-80% correct prediction rate). The sensitivity analysis indicates that the result is quite robust.

Even though premium trucks are more expensive than standard trucks, they have better performance, and longer life. If a freight car is heavily used, premium trucks can save about 5% of life cycle cost compared to standard trucks if replacement upon failure and CBM are implemented, and they are competitive with standard trucks under periodic replacement policy. Another advantage that premium trucks have over standard trucks, is that premium trucks will cause less freight damage than standard trucks because of their better performance. If the freight has high value, then this becomes a significant favor for premium trucks.

6.3. Future Research

Future research can take at least three directions. The first one is to continue to improve the inspection results. Even with the considerable amount effort that has put into this topic, the overall correct prediction rate is under 90%, and the false alarm rate is very high. A More balanced data set covering trucks with a broader range of conditions is needed to improve this result.

New technology can also play an important role. New technology can be adopted to effectively monitor the performance of truck, which would allow better prediction of the internal condition of truck.

The second direction is to conduct more research to better understand the complicated inter-relationships among the life cycle cost components. In this research, the relationship among truck life, operating cost, and truck deterioration rates are hypothesized based on researchers' knowledge, and railroad engineers' experience. These are reasonable hypotheses, but they are not directly derived from any real data. More research can be done to calibrate these relations from historical maintenance databases.

The last direction is more related to implementation. Research can be done to determine what it will take for a railroad or freight car owner to implement this maintenance strategy. It is certain there are many obstacles, such as how to enhance existing information systems to maintain and update the necessary maintenance information for each truck, as well as monitoring the routing of cars and scheduling the necessary inspections.

Reference

American Steel Foundries, **Super Service Ride Control and Ride Control Trucks, Maintenance and Repair Manual**, 1994.

Barbera, F., Schneider, H., and Kelle, P., "A Condition Based Maintenance Model with Exponential Failures and Fixed Inspection Intervals," **Journal of the Operational Research Society**, Vol. 47, 1037-1045, 1996.

Barlow, R. E., Proschan, F., and Hunter, H, "Optimum Checking Procedures," **SIAM**, Vol. 11, 1078-1095, 1963.

Ben-Akiva, M. and Lerman, S., **Discrete Choice Analysis: Theory and Application to Travel Demand,** 1985.

Chang, Jiang, **Applying Two Statistical Models to Condition-Based Machinery Inspection and Maintenance - Railroad Car Truck Case**. Unpublished M.S.T. Thesis, Massachusetts Institute of Technology, 1995.

Christer, A. H., and Wang, W., "A Simple Condition Monitoring Model for A Direct Monitoring Process", **European Journal of Operational Research**, Vol. 82, 258-269, 1995.

Guins, T. S., "A Statistical Analysis of Roller Bearings," Paper presented to ASME Conference, Boston, 1987.

Guins, T. S. and J. Kyparesis, "Equipment Reliability Analysis Systems", Unpublished A.A.R. working paper, undated.

Hawthorne, V., "Effect of Maintenance Practices Upon Performance of Freight Car Railroad Trucks - Progress Report," **IEEE/ASME Joint Railroad Conference**, 1990.

Little, P., and Martland, C. D., **Improving Railroad Car Maintenance By Using Knowledge Based Systems**, M.I.T. Studies in Railroad Operations and Economics, Vol. 39, December, 1989.

Little, P., **Improving Railroad Freight Car Reliability Using A New Opportunistic Maintenance Heuristic and Other Information System Improvements**. Unpublished Ph.D. Thesis, Massachusetts Institute of Technology, 1991.

Manski, C. and McFadden, D., **Structural Analysis of Discrete Data with Econometric Applications**, 1990.

Martland, C. D., (series editor) (SROE), **Studies in Railroad Operations and Economics**, series of monographs and papers published jointly by the Association of American Railroads and the M.I.T. Rail Group.

Mckelvey, R., and Zavoina, W., "A Statistical Model for the Analysis of Ordinal Level Dependent Variable," **Journal of Mathematical Sociology**, Vol.4., 1975.

Morrison, A. S., **Screening in Chronic Disease**, Oxford University Press, New York, 1985.

Muller, Ch., Mandelblatt, J., Schecter, C. B., Power, E. J., Duffy, B. M., and Wagner, J.L., **Costs and Effectiveness of Cervical Cancer Screening in Elderly Women**, Office of Technology Assessment, Washington, D.C., Feb 1990.

Park, K. S., "Optimal Continuous Wear Limit Replacement Under Periodic Inspections," **IEEE Transactions On Reliability**, Vol. 36, 581-585, 1988.

Pindyck, R. S., and Rubinfeld, L. D., **Microeconomics**, Prentice Hall, Englewood Cliffs, New Jersey, 1995.

Read, D., and Kalay, S., "Initial Results of FAST/HAL Phase III Testing" **Technology Digest, TD 96-025, Association of American Railroads**, 1996.

Sengupta, B., "Inspection Procedures When Failure Symptoms are Delayed," **Operations Research**, 28, 768-776, 1980.

Shahani, A. K., and Crease, D. M., "Towards Models of Screening for Early Detection of Disease," **Advances in Applied Probability**, 9, 665-680, 1977.

Winston, W. L., **Operations Research**, Duxbury Press, Belmont, California, 1994.